First results from the current observation run of the LIGO-Virgo network of advanced gravitational waves detectors

Fiodor Sorrentino

GW170104: FACTSHEET

Background Images: time-frequency trace (top), H1 and L1 time series and maximum-likelihood binary black hole model (middle top), residuals between data and best-fit model (middle bottom), reconstructed waveforms from wavelet and binary black hole analyses (bottom)

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	04 Jan 2017
time	10:11:58.6 UTC
signal-to-noise ratio	13
false alarm rate	< 1 in 70,000 years
probability of astrophysical origin	> 0.99997
distance	490 to 1330 Mpc
redshift	0.10 to 0.25
likely orientation of the orbit	face-on/off
total mass	46 to 57 $M_\odot$
primary BH mass	25 to 40 $M_\odot$
secondary BH mass	13 to 25 $M_\odot$
mass ratio	0.36 to 0.94
remnant BH mass	44 to 54 $M_\odot$
remnant size	123 to 150 km
remnant area	1.9 to 2.8 x 10^5 km^2
effective spin parameter	-0.42 to 0.09
effective precession spin parameter	unconstrained

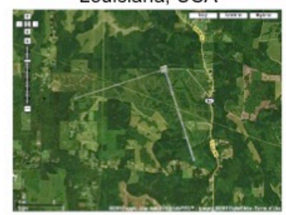
duration from 20 Hz	0.80 to 1.07 s
# of cycles from 20 Hz	27.3 to 33.6
signal arrival time delay	arrived at H1 3 ms before L1
credible region sky area	1200 sq. deg.
# of detection pipelines	3
peak GW strain	~ 5 × 10^{-22}
peak displacement of interferometer arm	~ ± 1 am
frequency at peak GW strain	160 to 199 Hz
wavelength at peak GW strain	1510 to 1880 km
peak speed of BHs	~ 0.6 *c*
peak GW luminosity	1.8 to 3.8 × 10^{56} erg s^{-1}
radiated GW energy	1.3 to 2.6 $M_\odot$
remnant ringdown freq.	297 to 373 Hz
remnant ringdown duration	7.9 to 10.1 ms
number of ringdown cycles	2.6 to 3.4
consistent with general relativity?	passes all tests performed
graviton mass combined bound	≤ 7.7 x 10^{-23} eV/c^2
evidence for dispersion of GWs	none

Parameter ranges correspond to 90% credible intervals.
Acronyms: L1/H1=LIGO Livingston/Hanford, Mpc=Megaparsec=3.2 million lightyears, am=attometer=10^{-18} m, $M_\odot$=1 solar mass=2 x 10^{30} kg

LIGO/Virgo results from the first run of the Advanced gravitational waves detectors

Gianluca Gemme - *INFN Genova*
on behalf of the LIGO Scientific Collaboration and the Virgo Collaboration

LIGO Livingston Observatory
Louisiana, USA



Virgo, Cascina, Italy

LIGO Hanford Observatory
Washington, USA

A.Chincarini

the birth of gravitational waves astronomy

an overview of the latest LIGO-VIRGO observational run

Outline

- Summary of the aLIGO O1 & O2 results
  - GW170104
  - Astrophysical implications
  - Tests of GR and quantum gravity
- Perspectives for GW observation
  - Short term: remaining part of O2, towards O3
  - Medium term: reaching the limits of 2nd generation network
  - Long term: LISA, ET, other technologies
- Status of Advanced Virgo
  - Design sensitivity
  - Main technical issues
  - Current status
  - Future upgrades

SUMMARY OF THE O1 & O2 RESULTS

GW170104

PRL **118,** 221101 (2017) PHYSICAL REVIEW LETTERS week ending 2 JUNE 2017

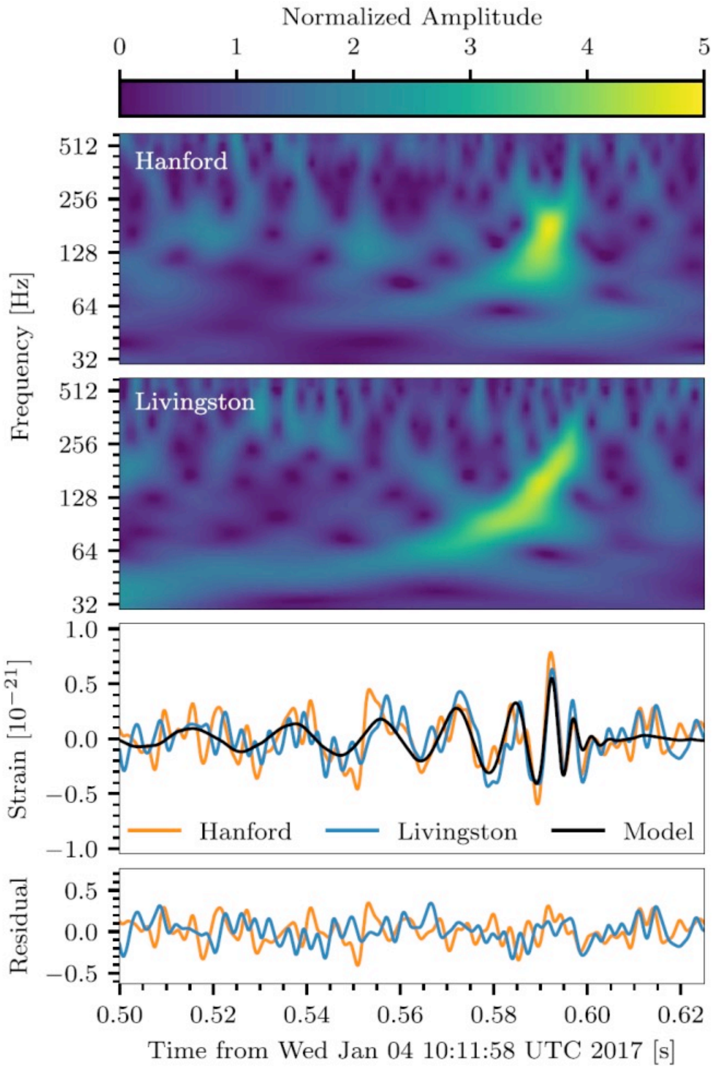
GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2

B. P. Abbott *et al.*[*]
(LIGO Scientific and Virgo Collaboration)
(Received 9 May 2017; published 1 June 2017)

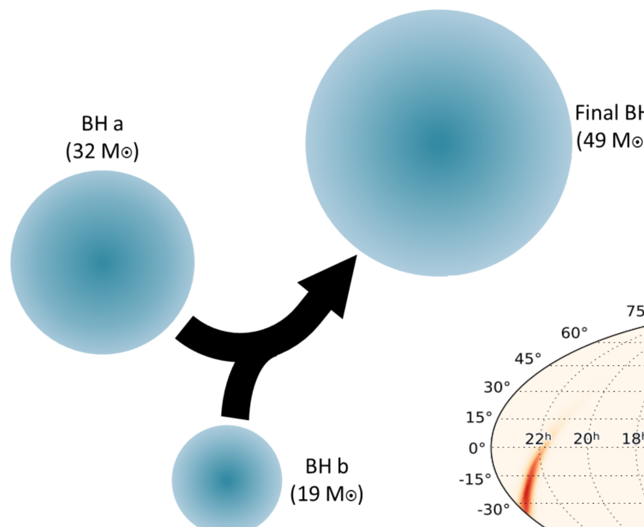
We describe the observation of GW170104, a gravitational-wave signal produced by the coalescence of a pair of stellar-mass black holes. The signal was measured on January 4, 2017 at 10:11:58.6 UTC by the twin advanced detectors of the Laser Interferometer Gravitational-Wave Observatory during their second observing run, with a network signal-to-noise ratio of 13 and a false alarm rate less than 1 in 70 000 years. The inferred component black hole masses are $31.2^{+8.4}_{-6.0} M_\odot$ and $19.4^{+5.3}_{-5.9} M_\odot$ (at the 90% credible level). The black hole spins are best constrained through measurement of the effective inspiral spin parameter, a mass-weighted combination of the spin components perpendicular to the orbital plane, $\chi_{\rm eff} = -0.12^{+0.21}_{-0.30}$. This result implies that spin configurations with both component spins positively aligned with the orbital angular momentum are disfavored. The source luminosity distance is 880^{+450}_{-390} Mpc corresponding to a redshift of $z = 0.18^{+0.08}_{-0.07}$. We constrain the magnitude of modifications to the gravitational-wave dispersion relation and perform null tests of general relativity. Assuming that gravitons are dispersed in vacuum like massive particles, we bound the graviton mass to $m_g \leq 7.7 \times 10^{-23}$ eV$/c^2$. In all cases, we find that GW170104 is consistent with general relativity.

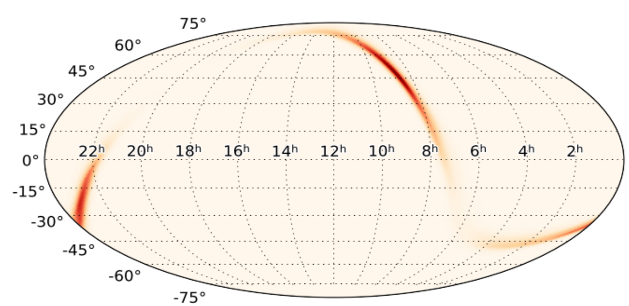
DOI: 10.1103/PhysRevLett.118.221101

GW170104

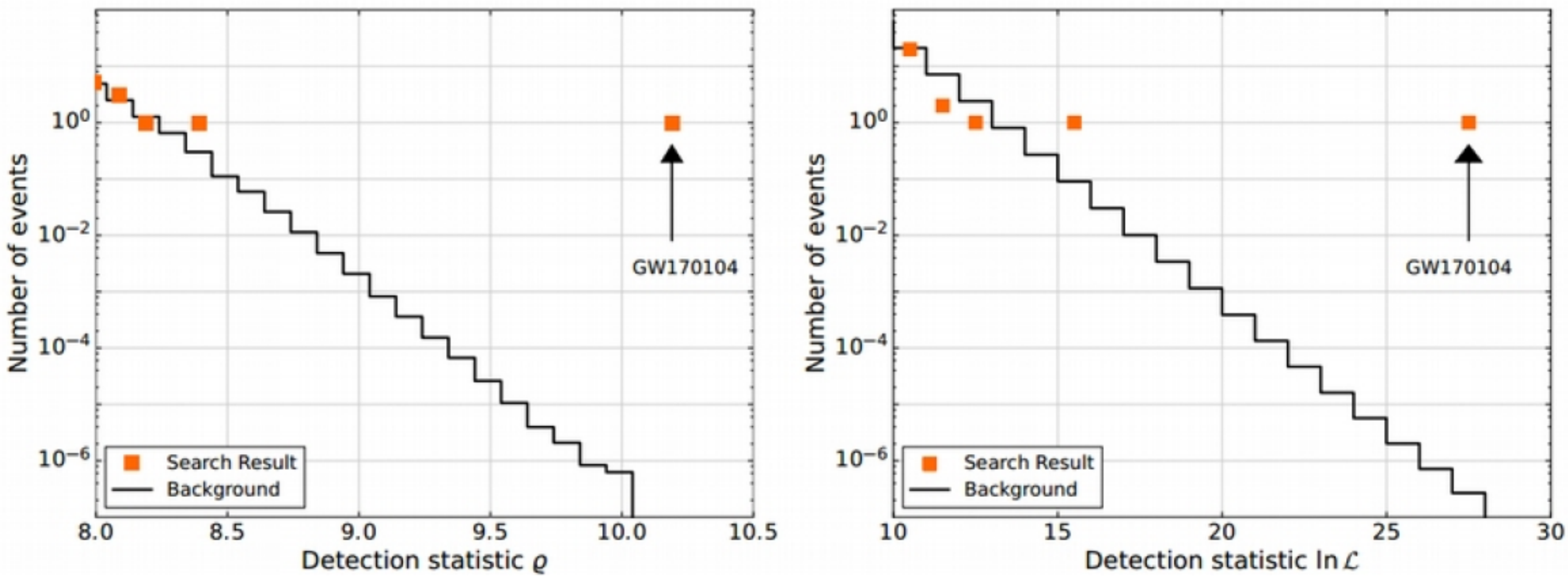


Primary black hole mass m_1	$31.2^{+8.4}_{-6.0} M_\odot$
Secondary black hole mass m_2	$19.4^{+5.3}_{-5.9} M_\odot$
Chirp mass $\mathcal{M}$	$21.1^{+2.4}_{-2.7} M_\odot$
Total mass M	$50.7^{+5.9}_{-5.0} M_\odot$
Final black hole mass M_f	$48.7^{+5.7}_{-4.6} M_\odot$
Radiated energy $E_{\rm rad}$	$2.0^{+0.6}_{-0.7} M_\odot c^2$
Peak luminosity $\ell_{\rm peak}$	$3.1^{+0.7}_{-1.3} \times 10^{56} \mathrm{erg\,s^{-1}}$
Effective inspiral spin parameter $\chi_{\rm eff}$	$-0.12^{+0.21}_{-0.30}$
Final black hole spin a_f	$0.64^{+0.09}_{-0.20}$
Luminosity distance D_L	880^{+450}_{-390} Mpc
Source redshift z	$0.18^{+0.08}_{-0.07}$



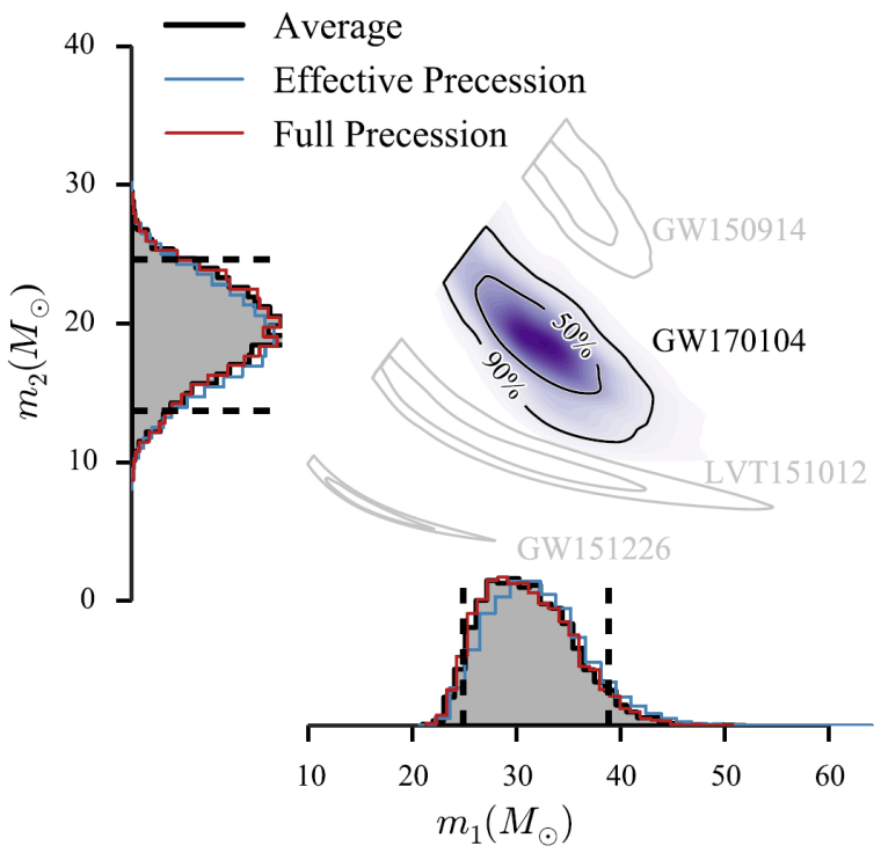


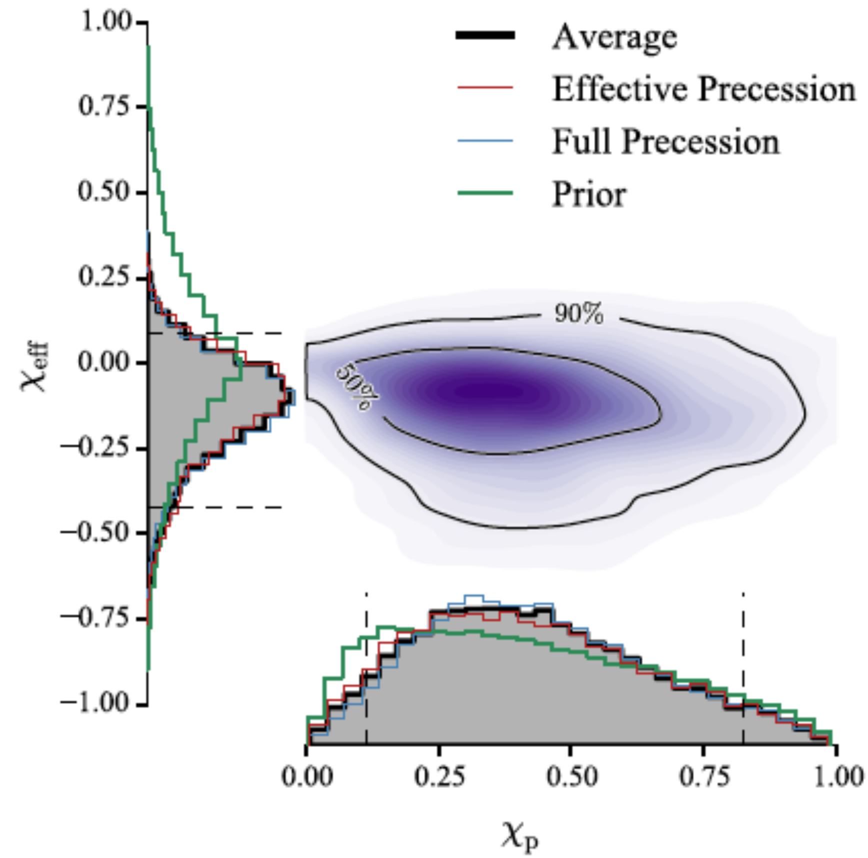
GW170104: search results



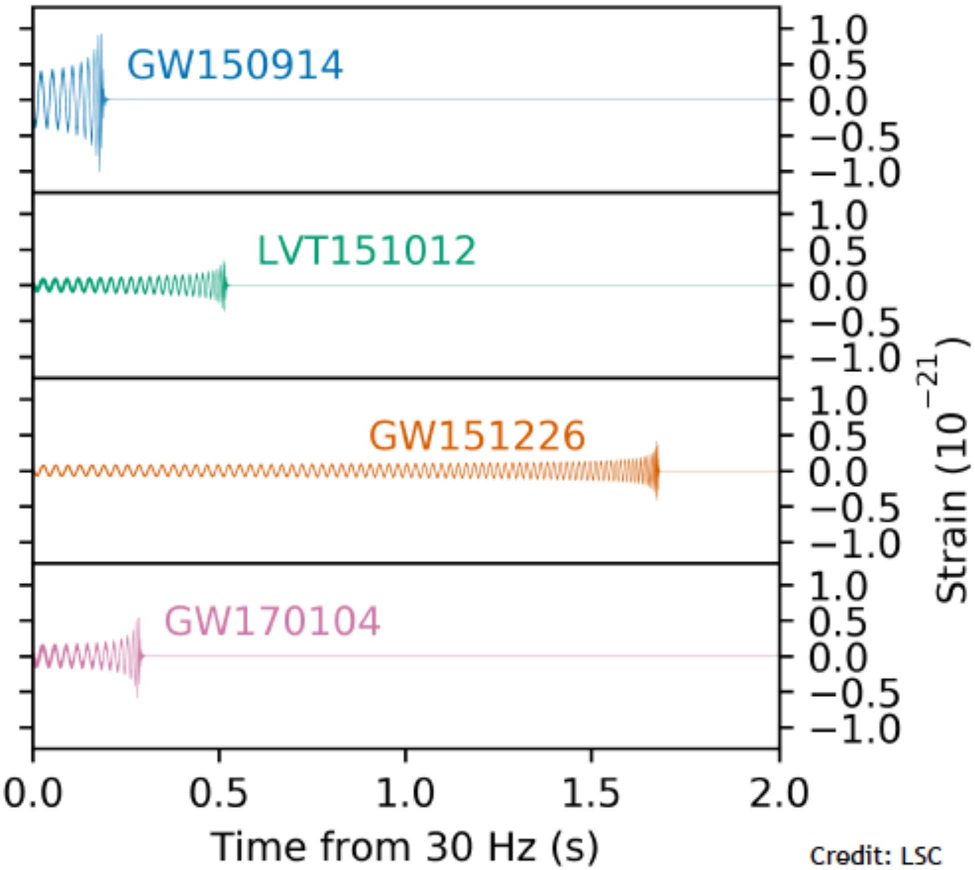
Results from two independent searches of the binary coalescence. The histogram shows the number of candidate events (orange markers) in the 5.5 days of coincident data and the expected background (black lines) as a function of the search detection statistic. At the detection statistic value assigned to GW170104, the search's false alarm rate is less than 1 in 70,000 years of coincident observing time. Right plot is from an independently-implemented analysis, where the detection statistic lnL is an approximate log likelihood ratio. The two search algorithms give consistent results.

GW170104: masses & spin

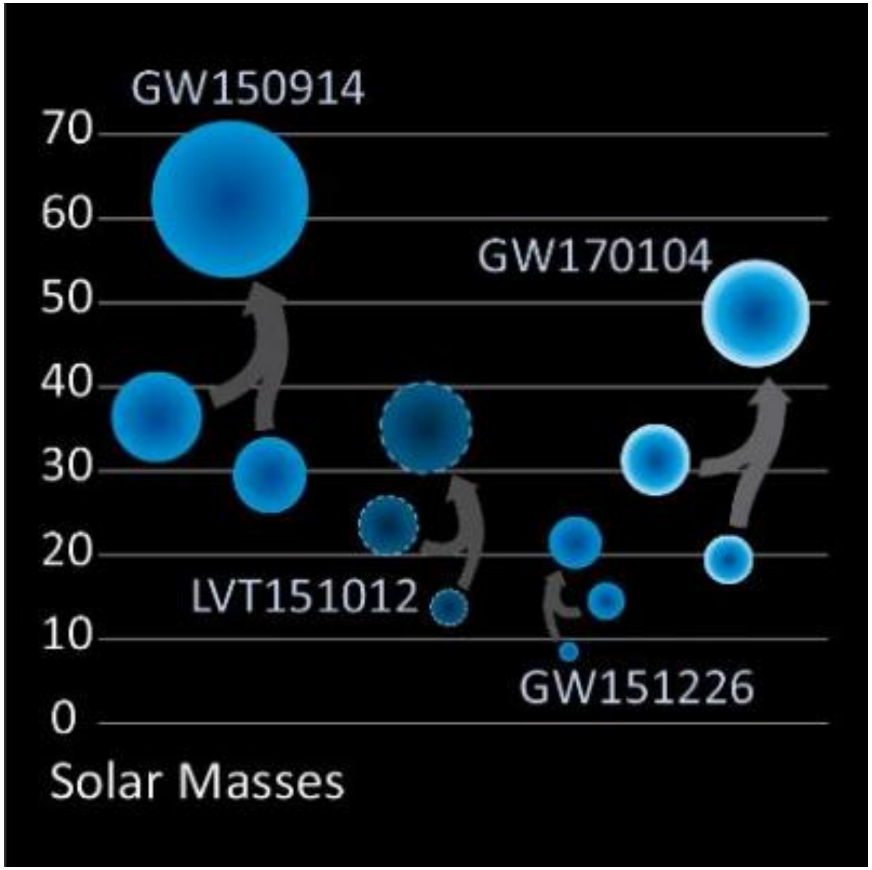




Summary of O1 & O2 results

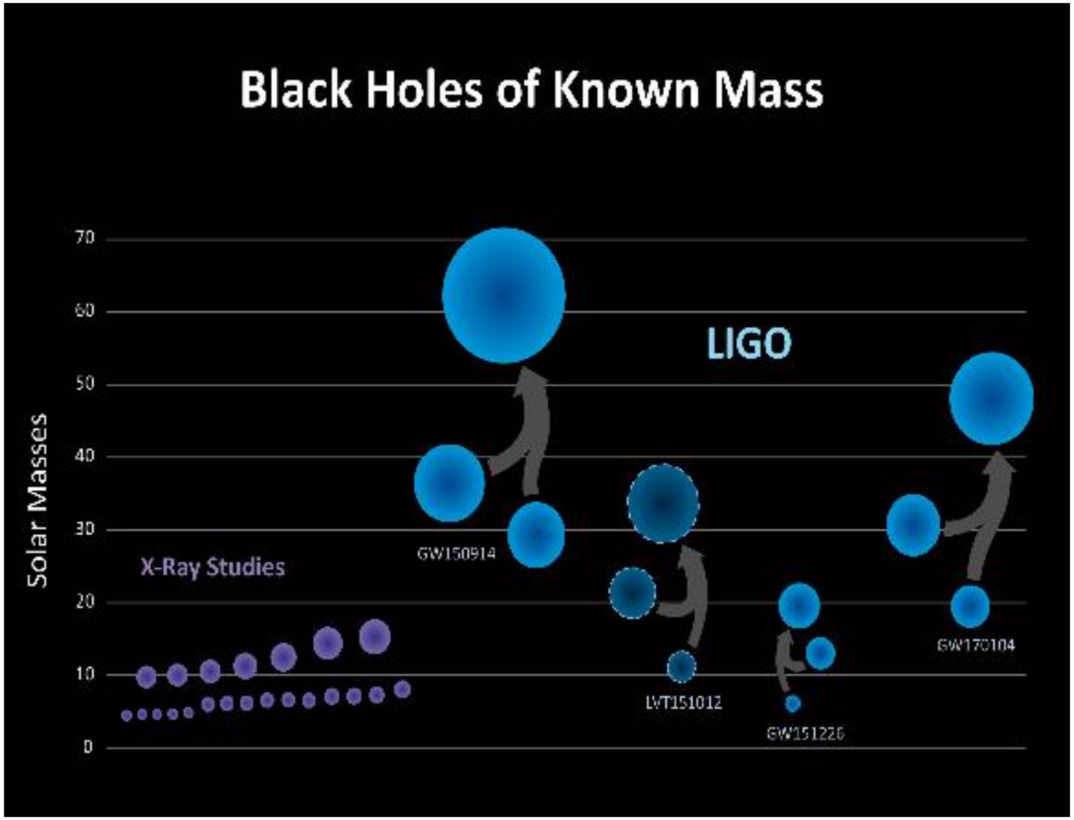


Credit: LSC

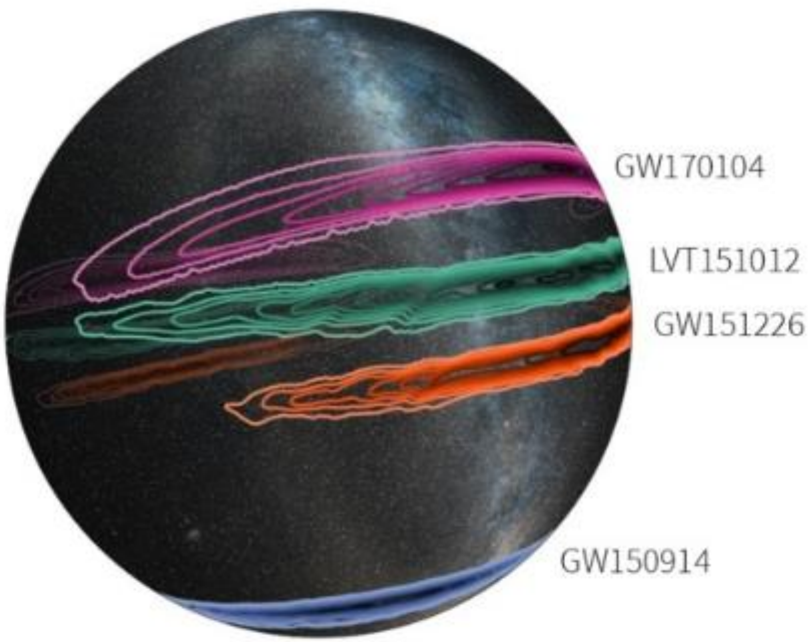


Astrophysical implications

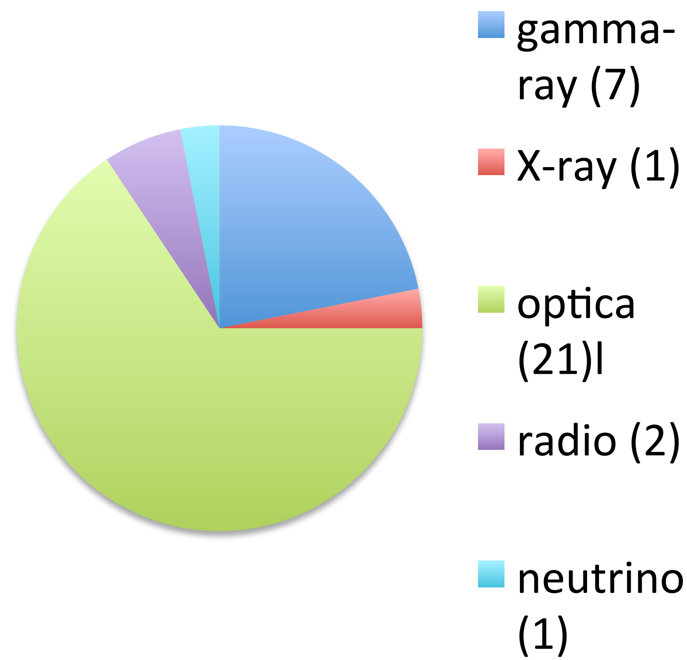
- Stellar binary black holes exist
- They form into binary pairs
- They merge within the lifetime of the universe
- The masses ($M > 20\ M_{\odot}$) are much larger than what was known about stellar mass Black Holes.
- Given the uncertainity regarding the measurement of the spins of the component BHs, the inferred range is consistent with both the scenarios for BBH formation:
  - Dynamical capture in dense stellar clusters
  - Isolated evolution in galactic fields



Sky localization, e.m. follow-up



32 Activated facilities

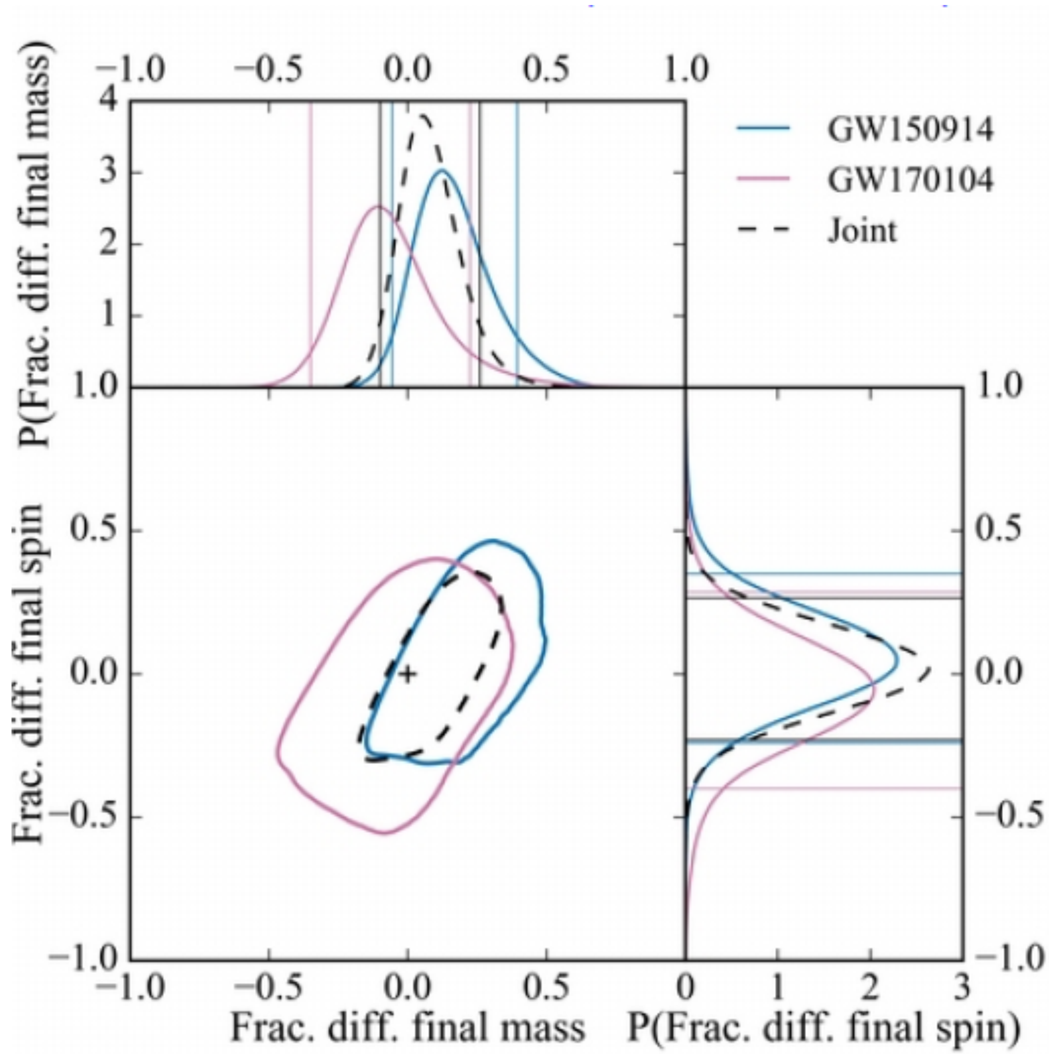


GR test from IMR consistency

Inspiral-merger-ringdown consistency: Estimating the final mass and spin from the initial (low frequency) and final (high frequency) stages of a BBH coalescence and checking their consistency.

The consistency of the initial and final estimates of final mass and spin implies that there is no evidence from this test for a departure of the signal from the predictions of GR for the coalescence of BBHs in quasicircular orbits.

We combine information from GW170104 and GW150914 to obtain tighter bounds on possible deviations from GR.



GR tests – dispersion term

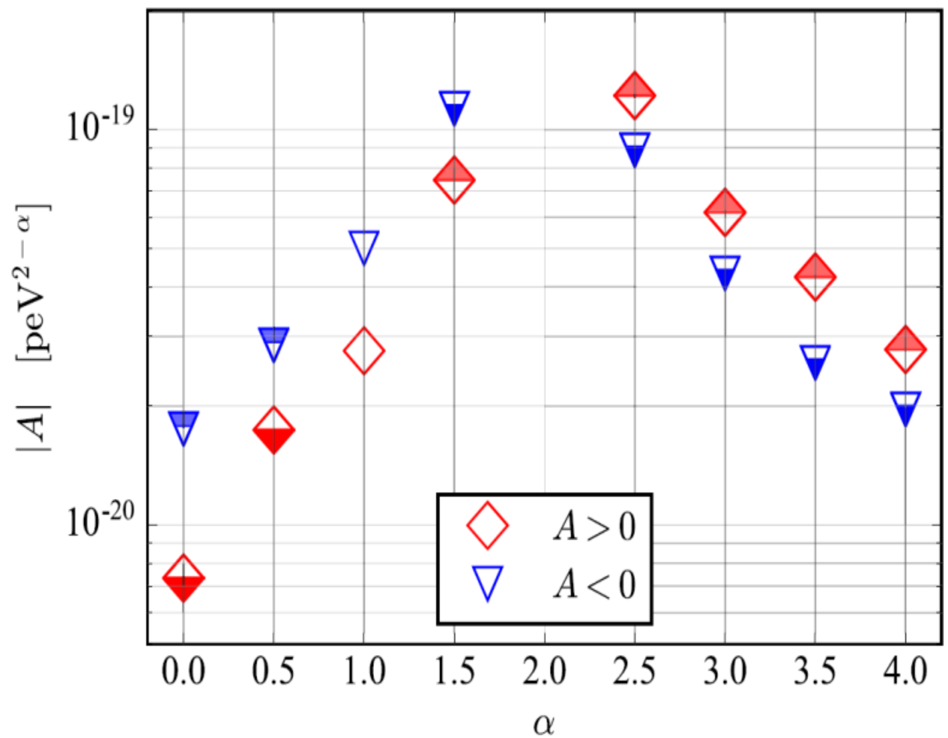
- In GR, there is no dispersion!

Add dispersion term of form

$$^2 = p^2c^2 + Ap^{\alpha}c^{\alpha}, \quad \alpha > 0$$

(E, p are energy, momenturm of g-w, A is amplitude of dispersion)

- Plot shows 90% upper bounds
- Null tests to quantify generic deviations from GR

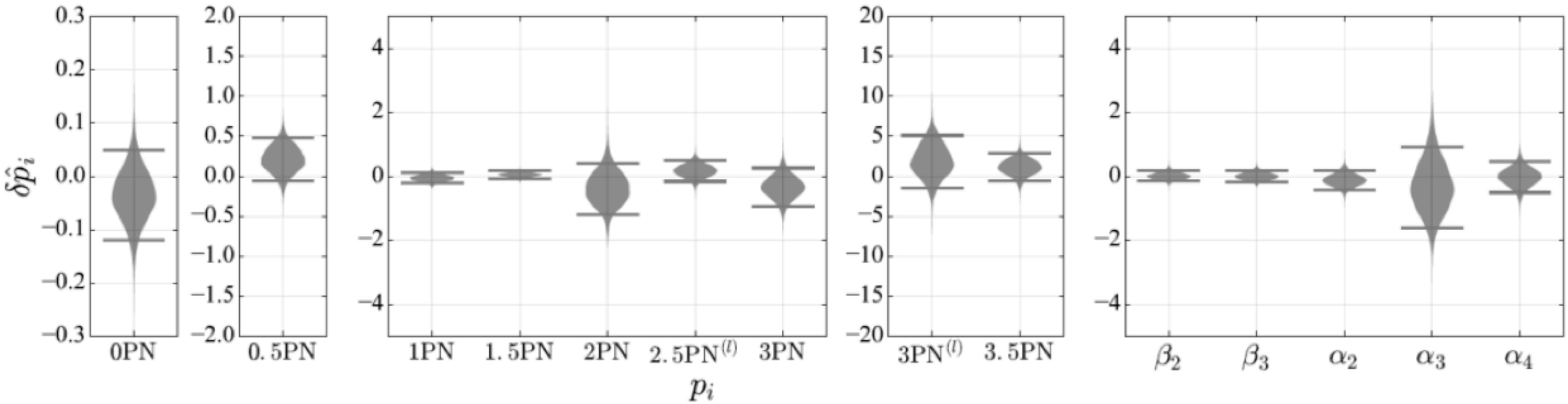


The upper bound on the mass of the graviton is improved and it is consistent with the theory of a massless graviton

$$m_g \leq 7.7 \times 10^{-23} eV/c^2$$

LSC & VIRGO: PRL 118.221101

GR tests – ppn terms

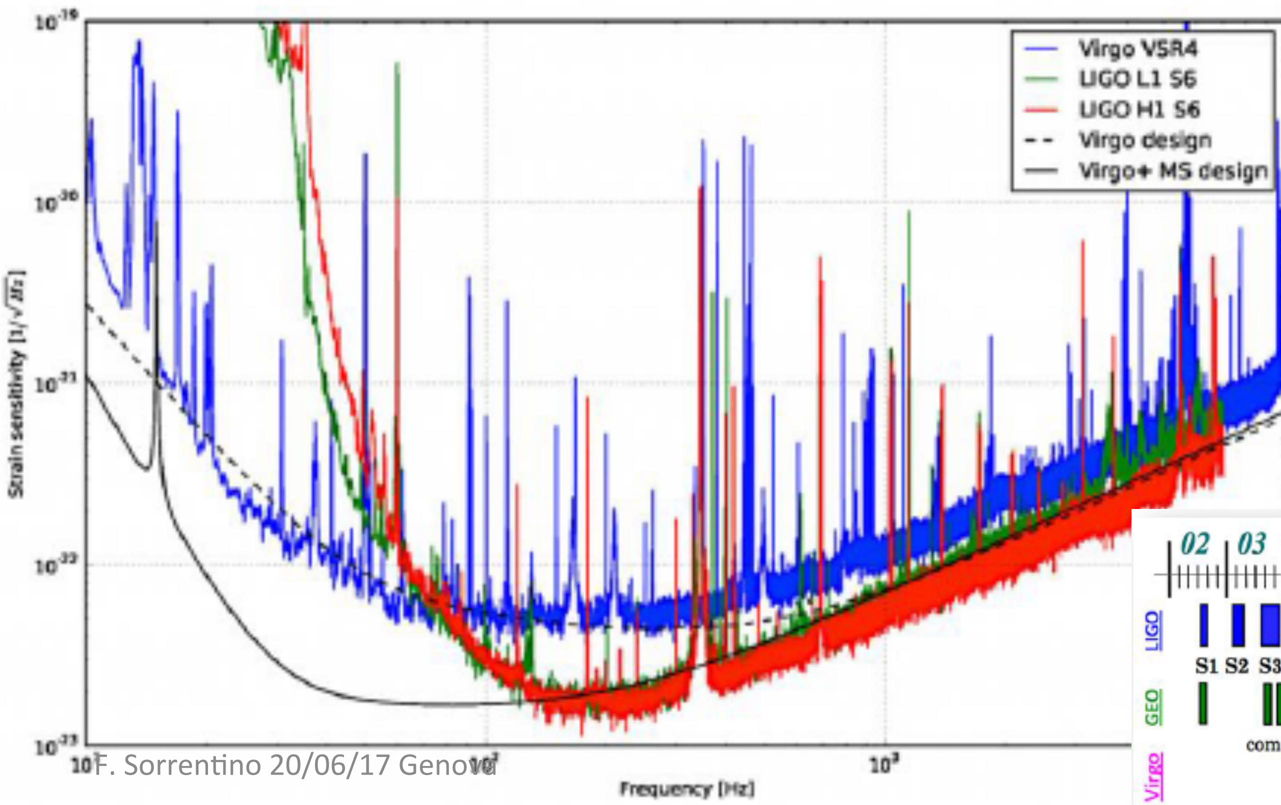


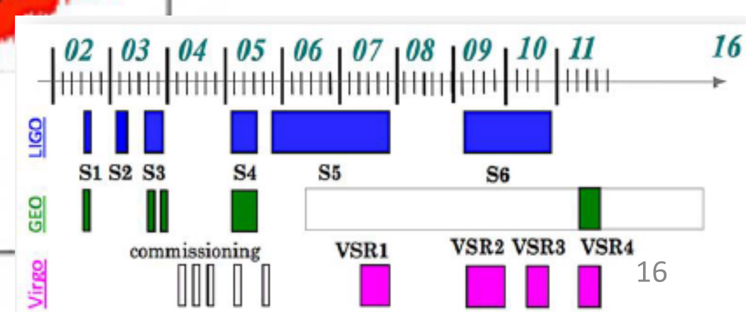
- GW150915, GW151226 and GW160104) combined
- Order of post-Newtonian expansion, then β and α parameters
- All are consistent with no deviations from GR

PERSPECTIVES FOR GW OBSERVATION

1st generation GW detectors

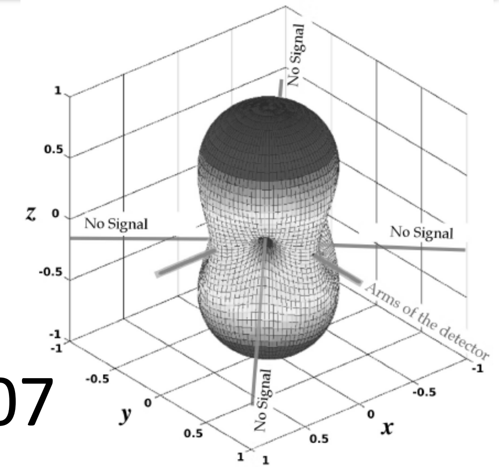
- LIGO, Virgo and GEO600 operated operated for about one decade, reaching their design sensitivities
- Demonstrated a reliable technology
  - duty cycle up to 80%
  - good knowledge of limiting noise sources
- No detections, but clear path towards 2nd generation antennas

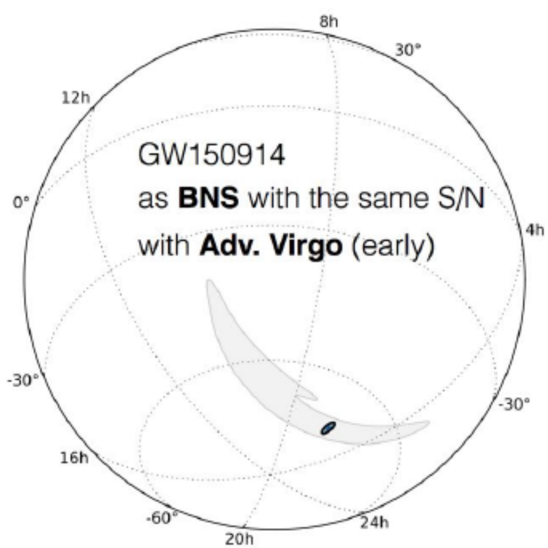




1st generation network

- GW antennas are poorly directional
- Source localization requires simultaneous distant detectors
- MoUs among LIGO, Virgo and GEO since 2007 for full exchange of data





from L SINGER, G1601468

Memorandum of Understanding

between

VIRGO

on one side

and the

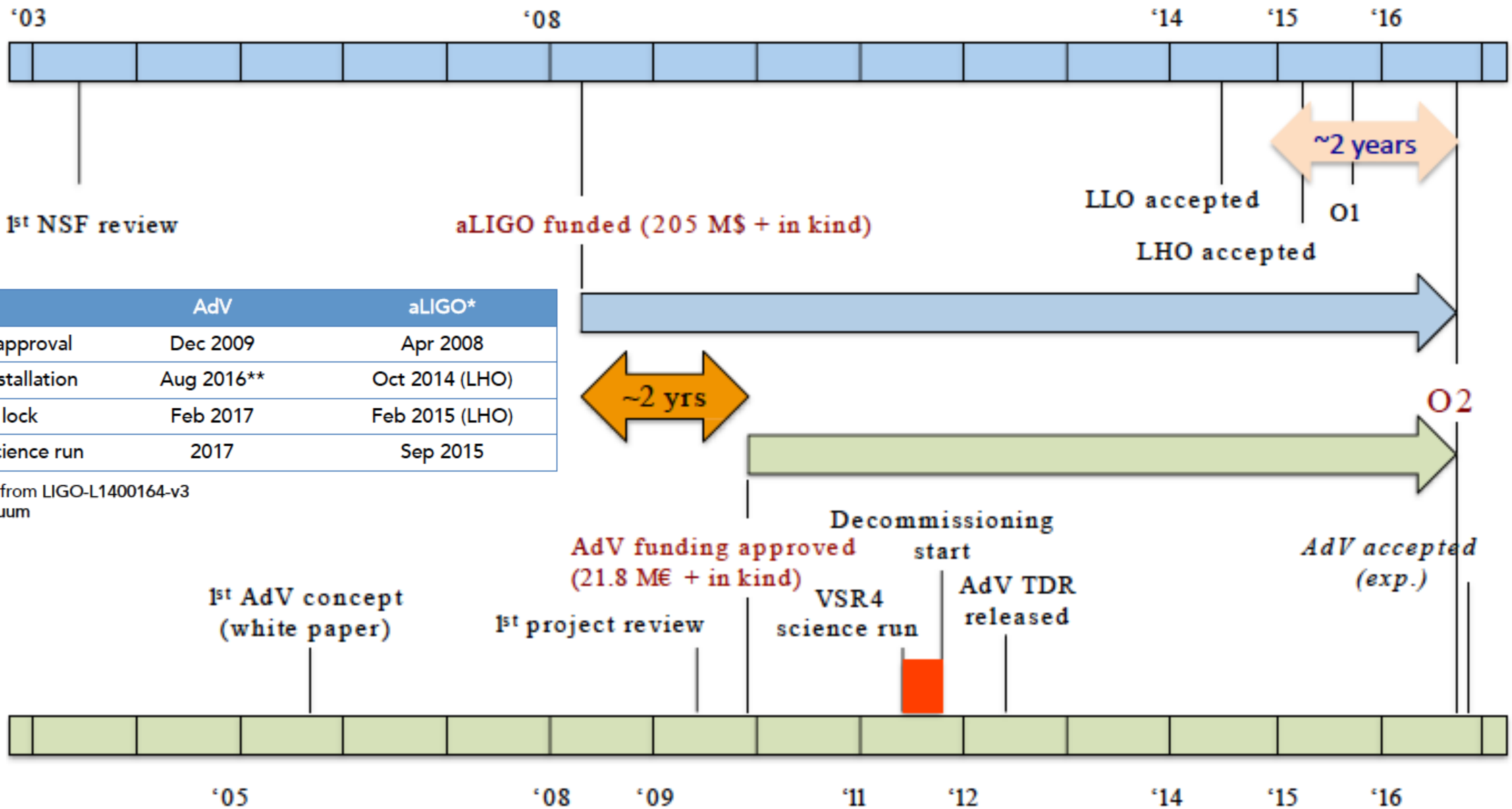
Laser Interferometer Gravitational Wave Observatory (LIGO)

on the other side

Purpose of agreement:

The purpose of this Memorandum of Understanding (MOU) is to establish and define a collaborative relationship between VIRGO on the one hand and the Laser Interferometer Gravitational Wave Observatory (LIGO) on the other hand in the use of the VIRGO, LIGO and GEO detectors based on laser interferometry to measure the distortions of the space between free masses induced by passing gravitational waves.

Towards advanced detectors

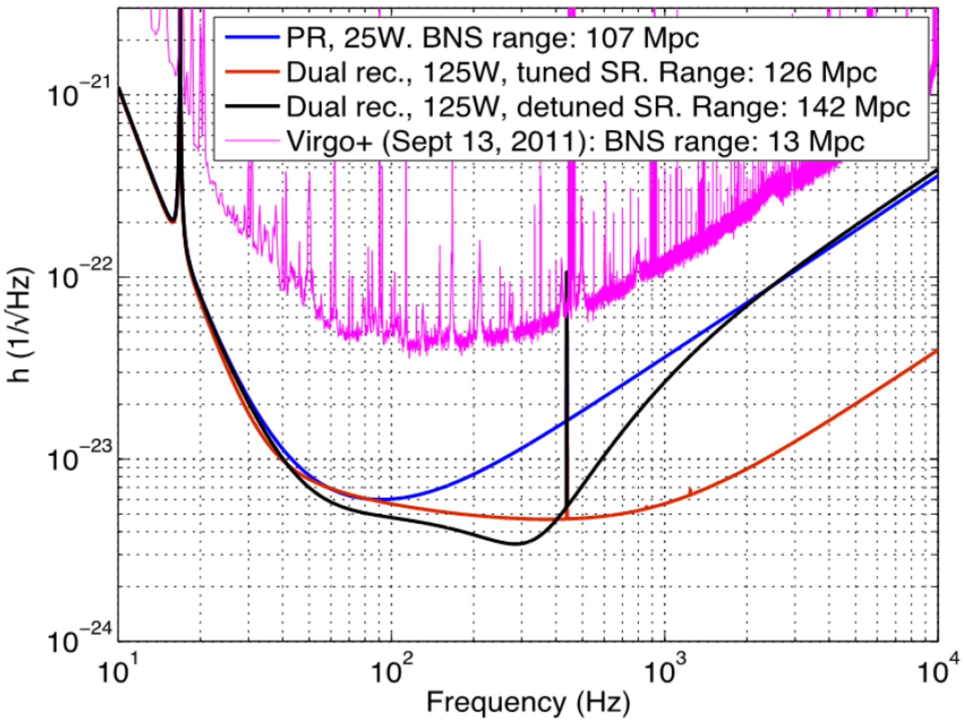


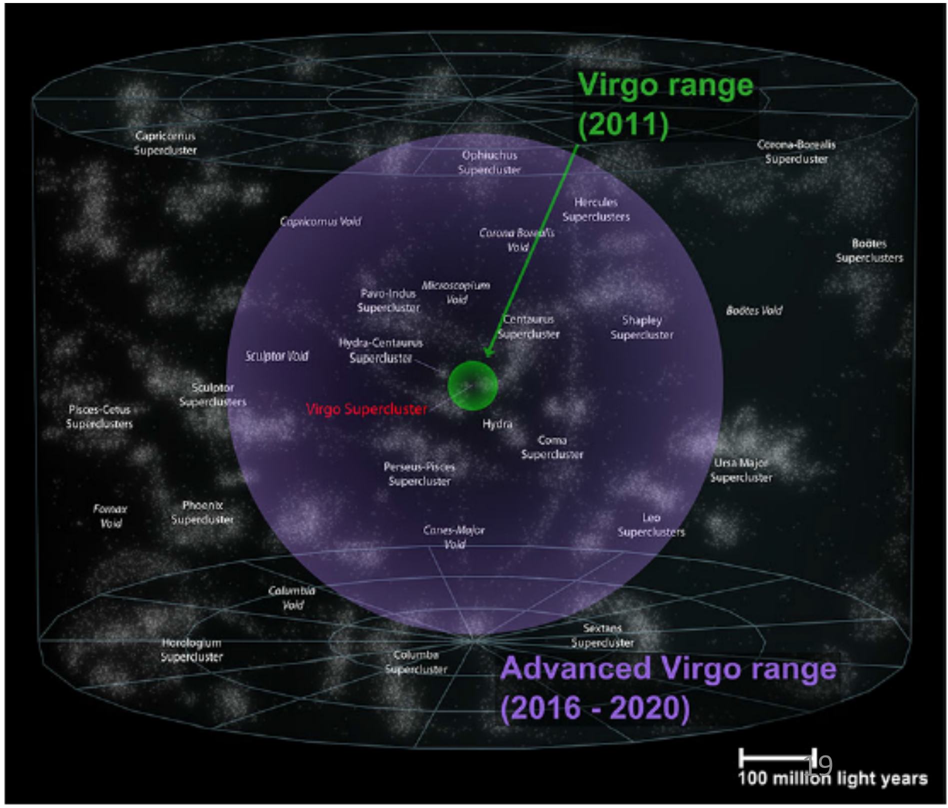
	AdV	aLIGO*
Date of approval	Dec 2009	Apr 2008
End of installation	Aug 2016**	Oct 2014 (LHO)
First lock	Feb 2017	Feb 2015 (LHO)
Start of science run	2017	Sep 2015

*LIGO data from LIGO-L1400164-v3
**ITF in vacuum

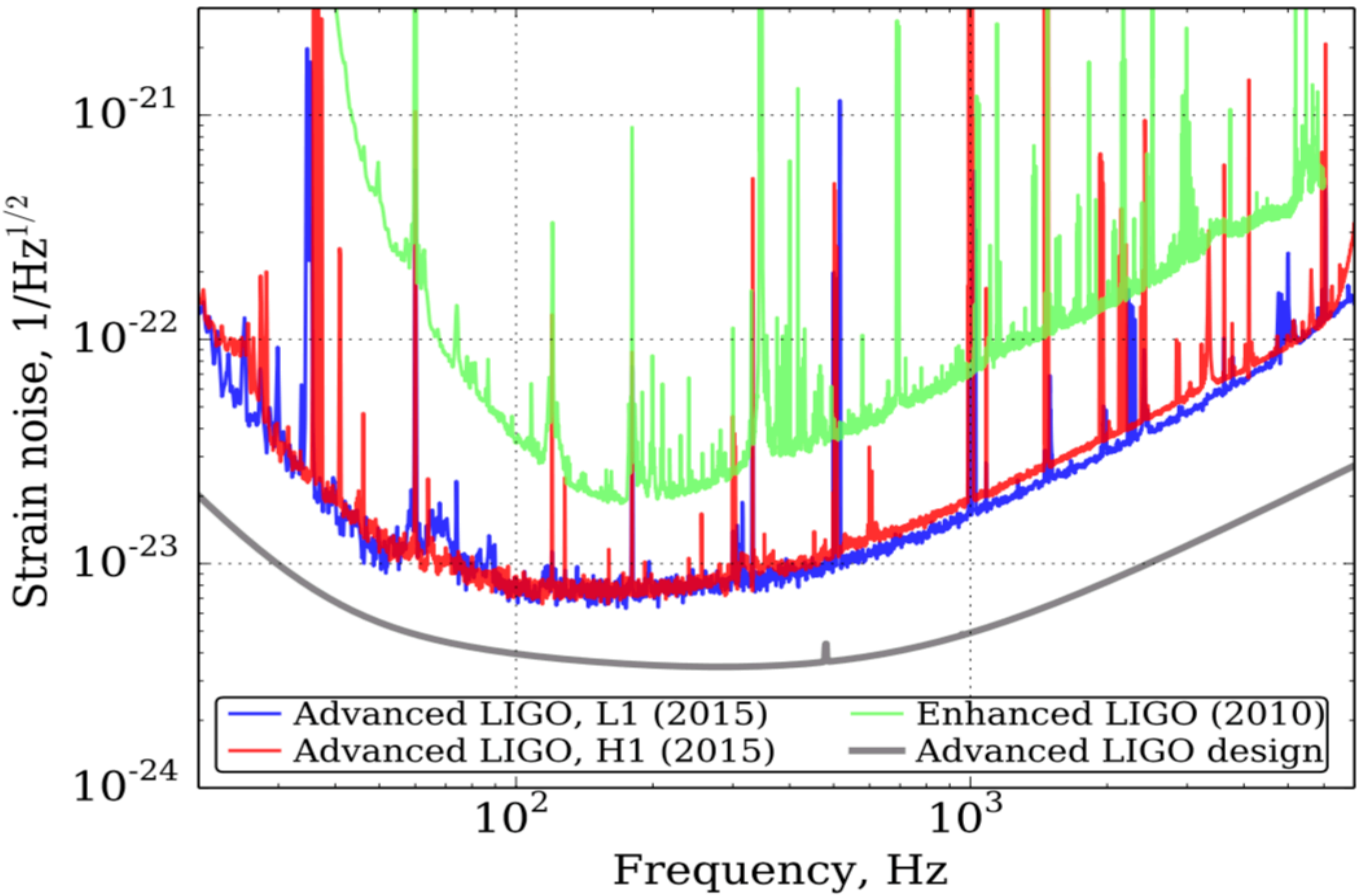
Advanced detectors

- 10 x sensitivity improvement over 1st generation detectors
- 1000 x increase of observation volume



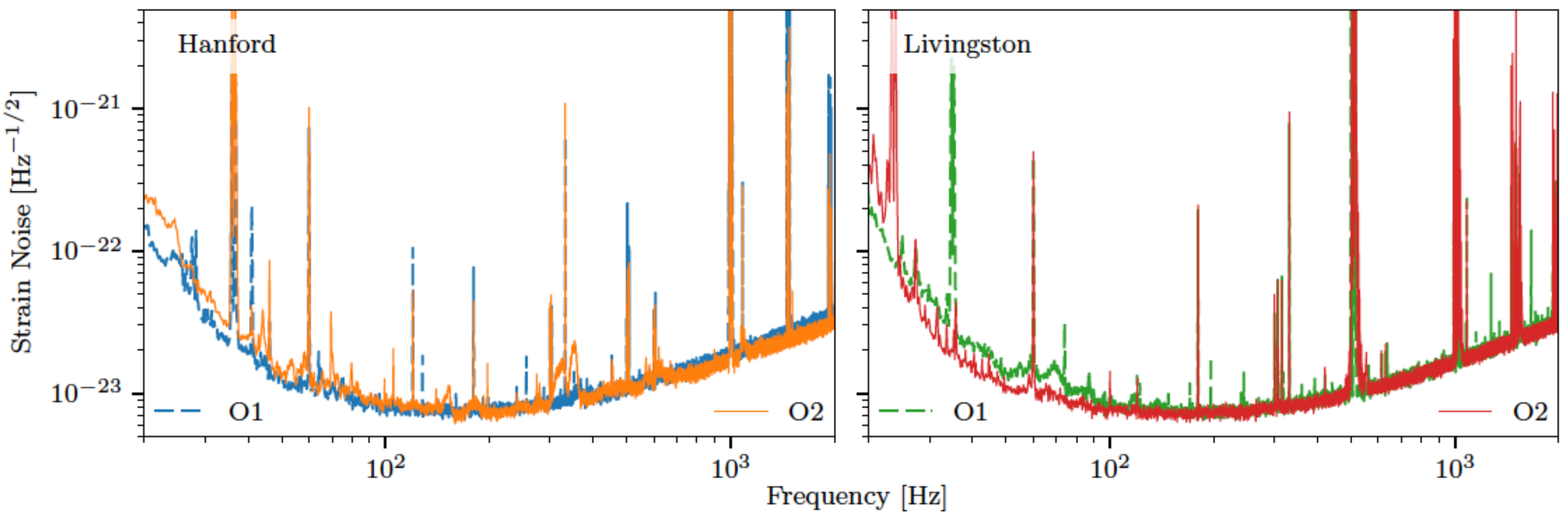


O1 Sensitivity

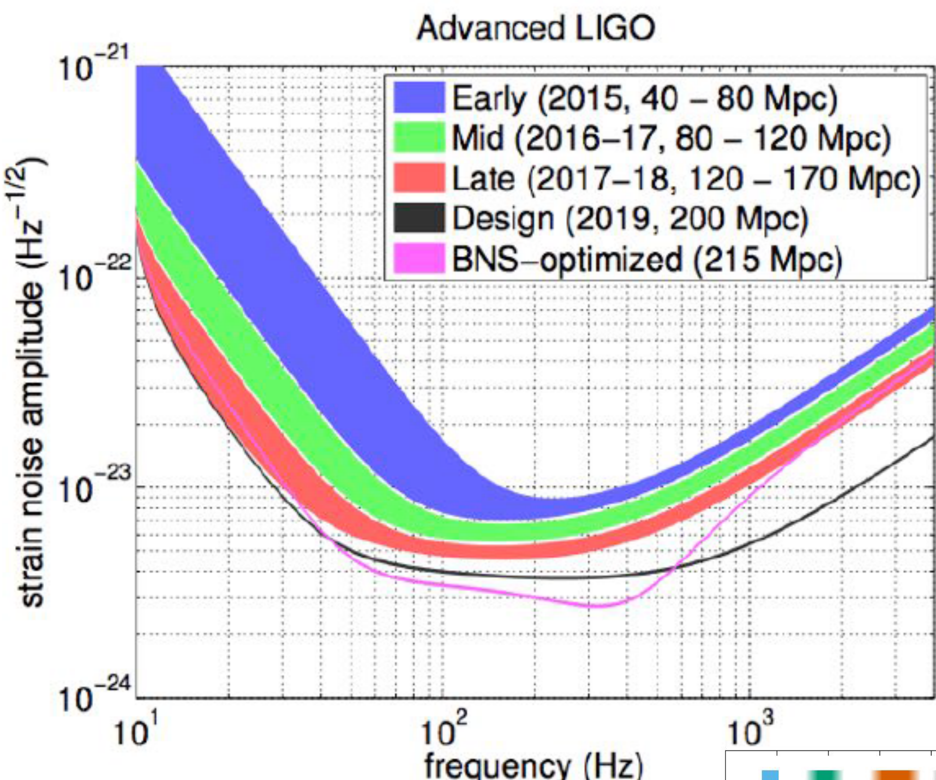


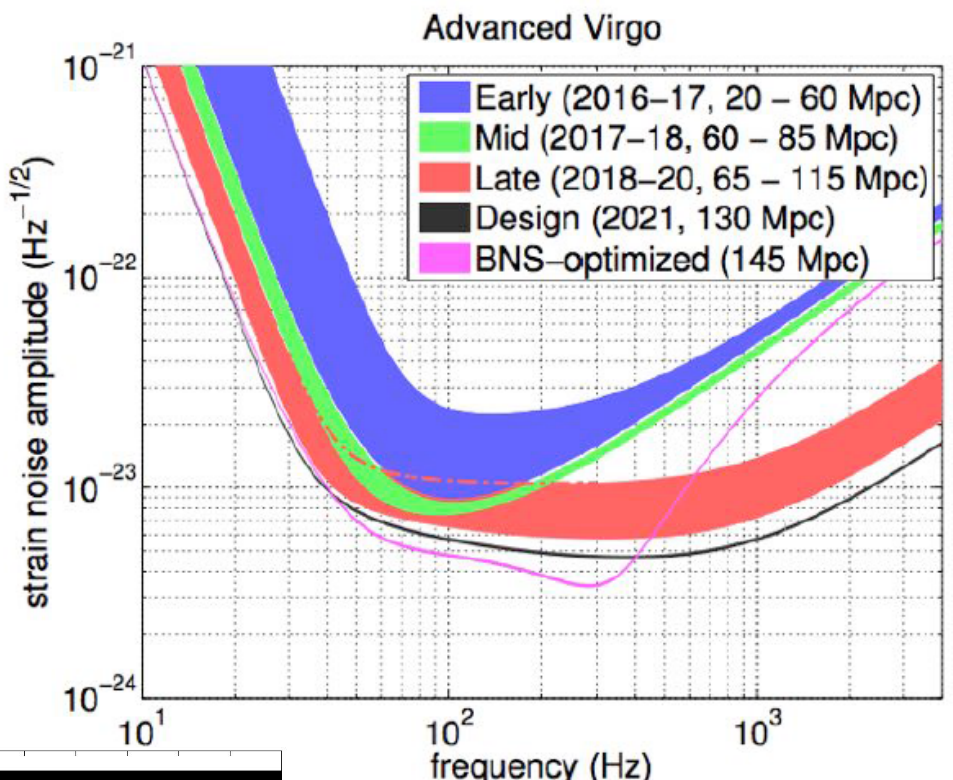
Phys. Rev. D 93, 112004 (2016)

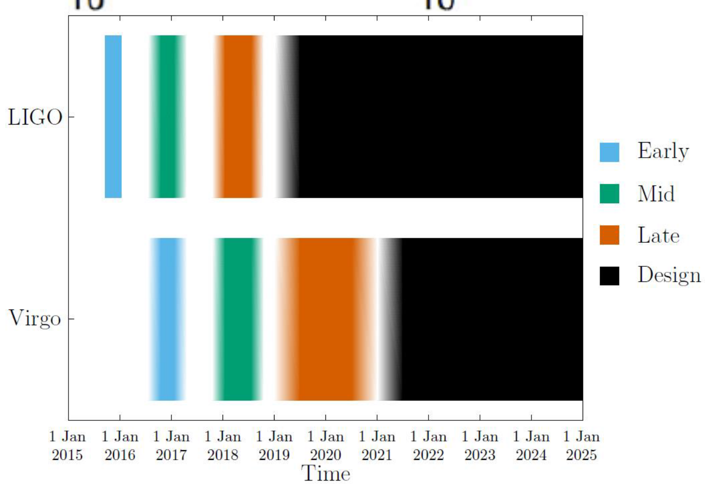
O2 vs O1 Sensitivity



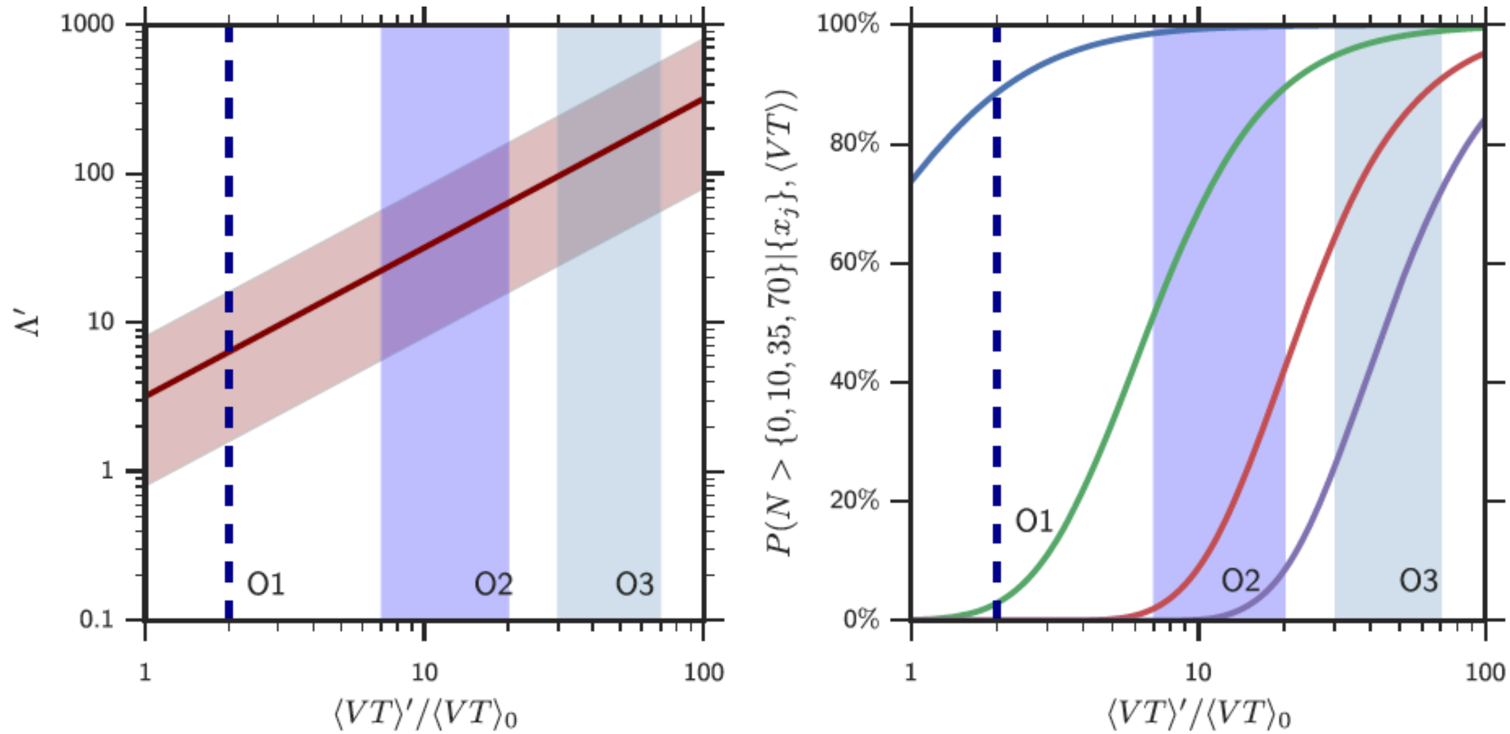
LIGO-Virgo Observing scenario







BBH detection rates

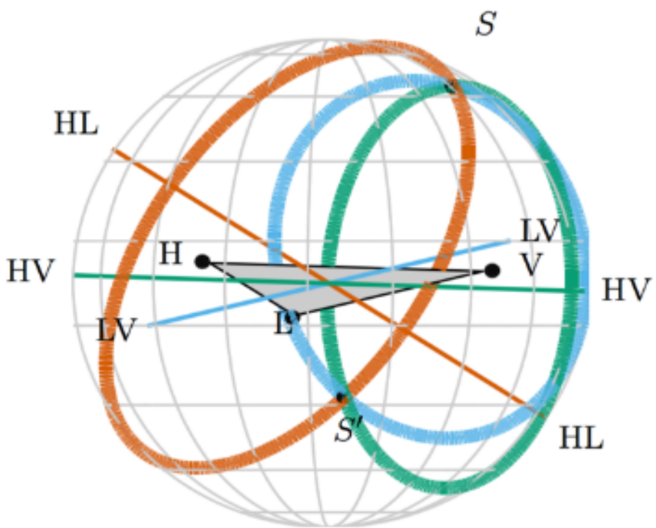


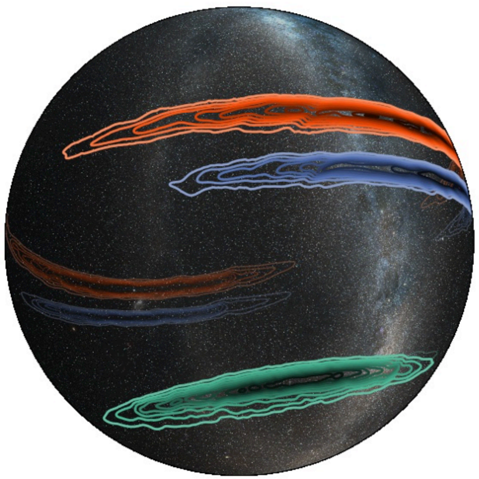
The updated merger rates for binary black hole coalescences are

12÷213 Gpc^{-3} yr^{-1}

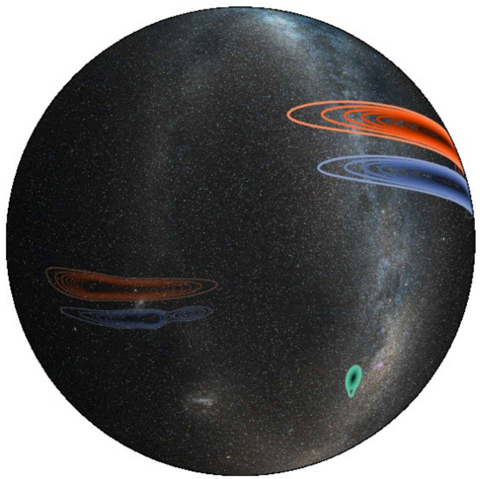
which is consistent with the range 9÷240 Gpc^{-3} yr^{-1} estimated from the first observing run

GW detector network



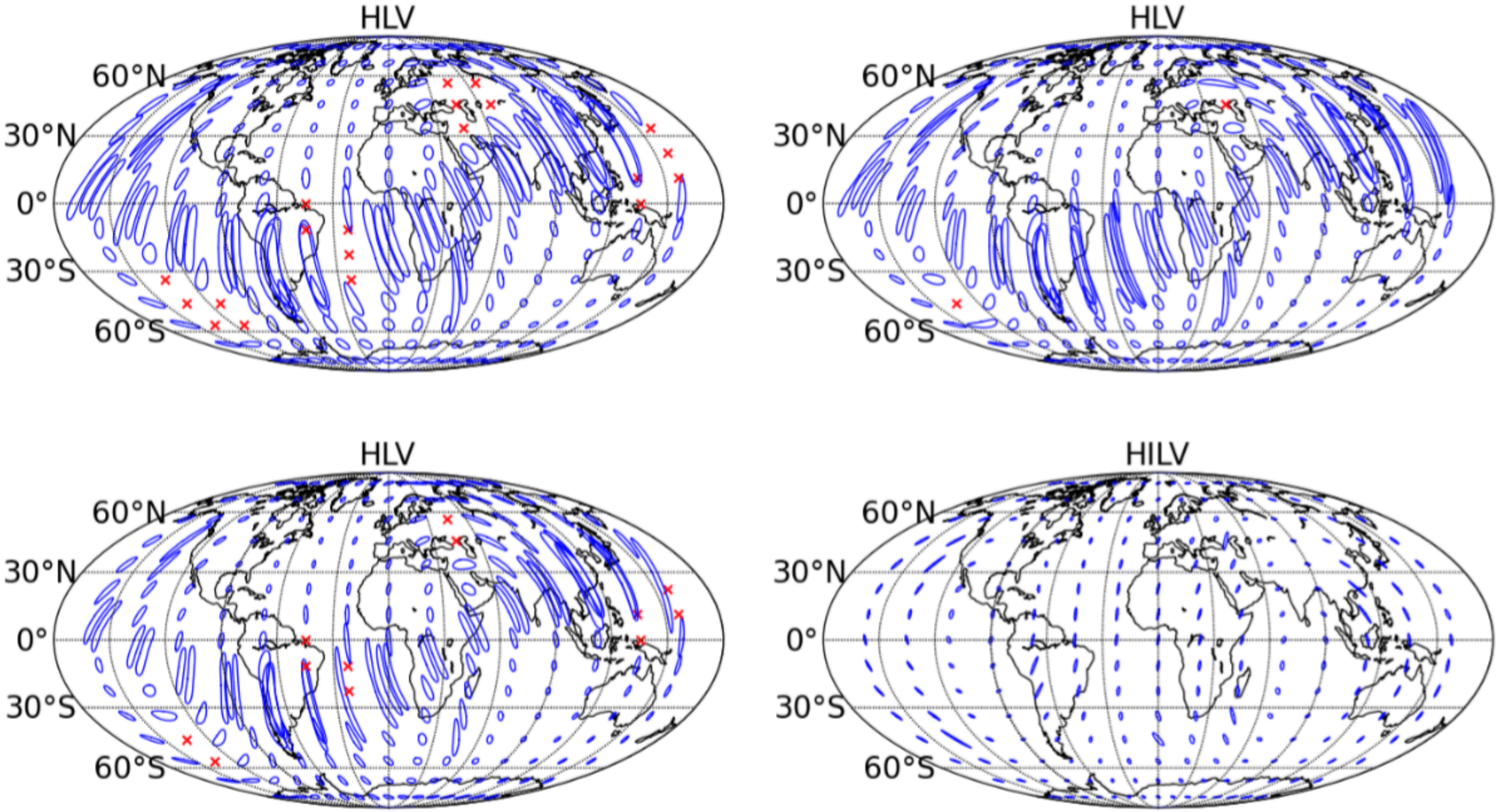


Without Virgo

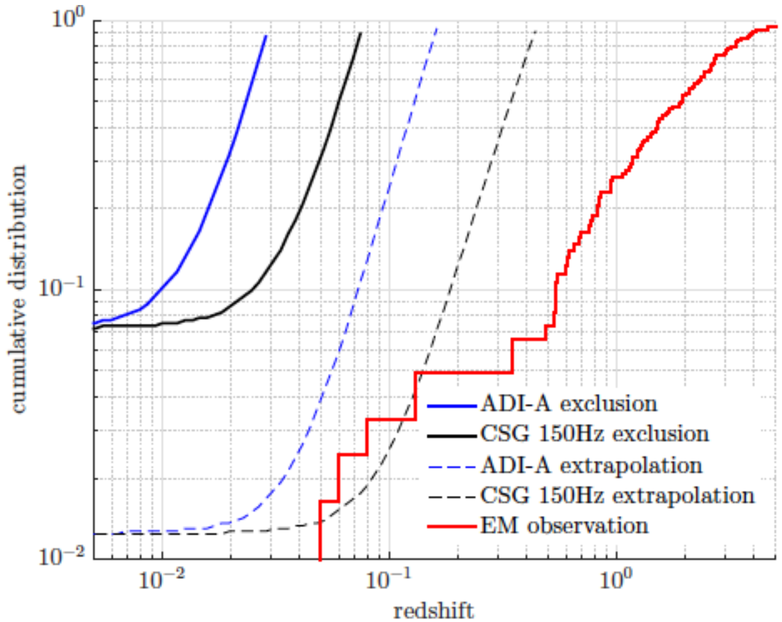


With Virgo

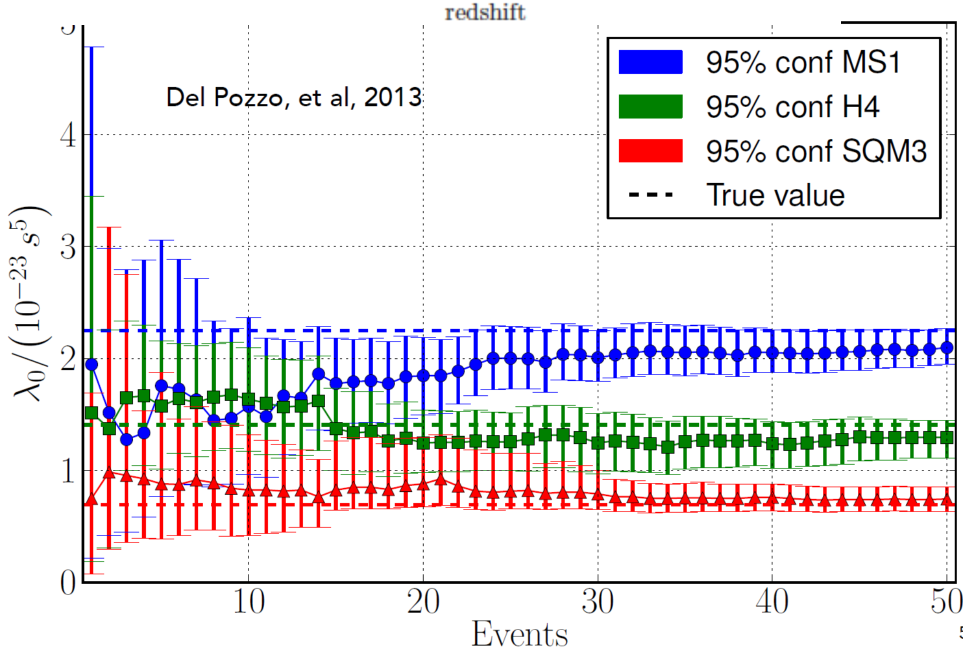
Source localization

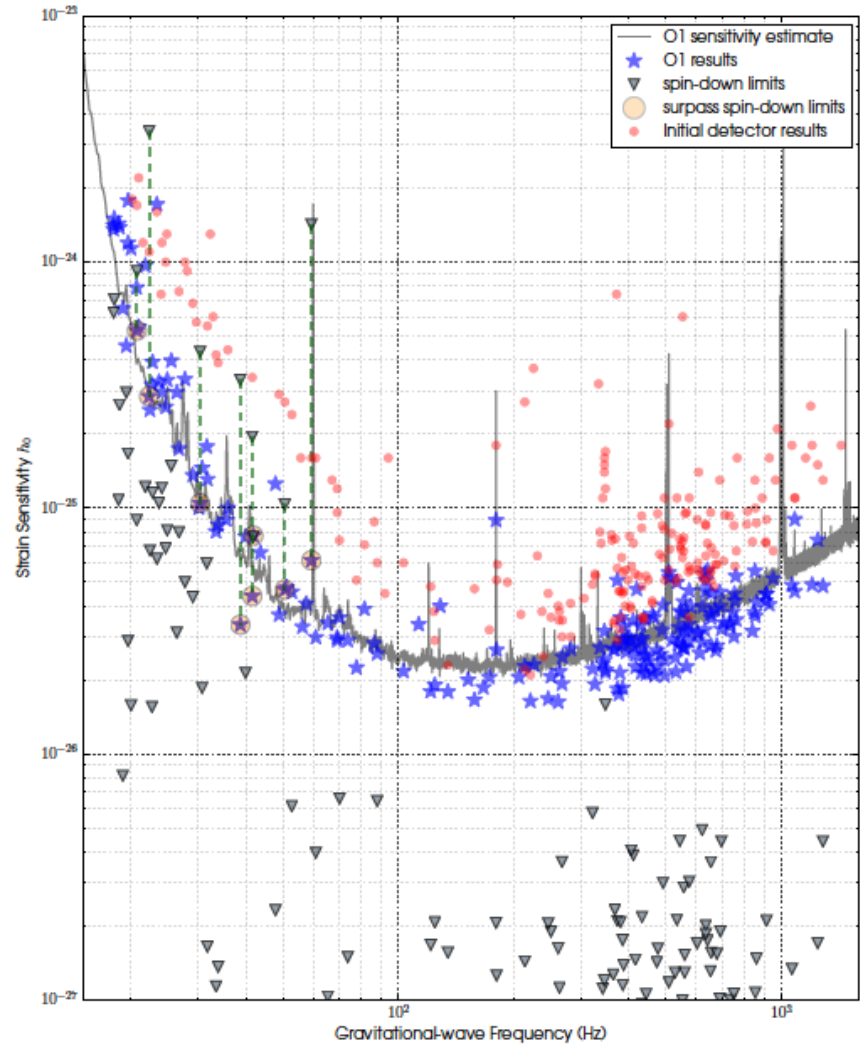


Other sources



GRB

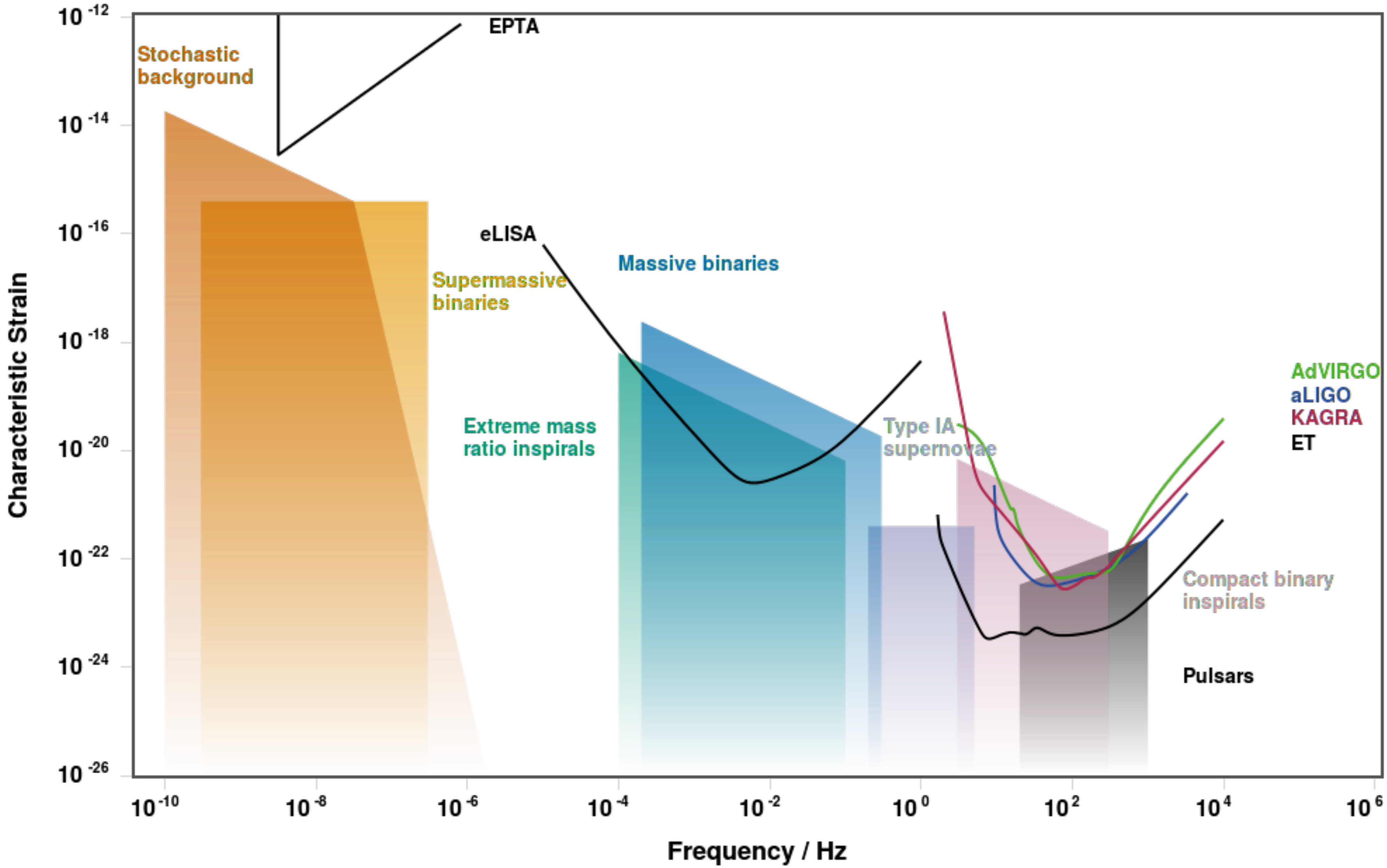




pulsars

Future GW detectors network

Future GW detectors network



STATUS OF ADVANCED VIRGO

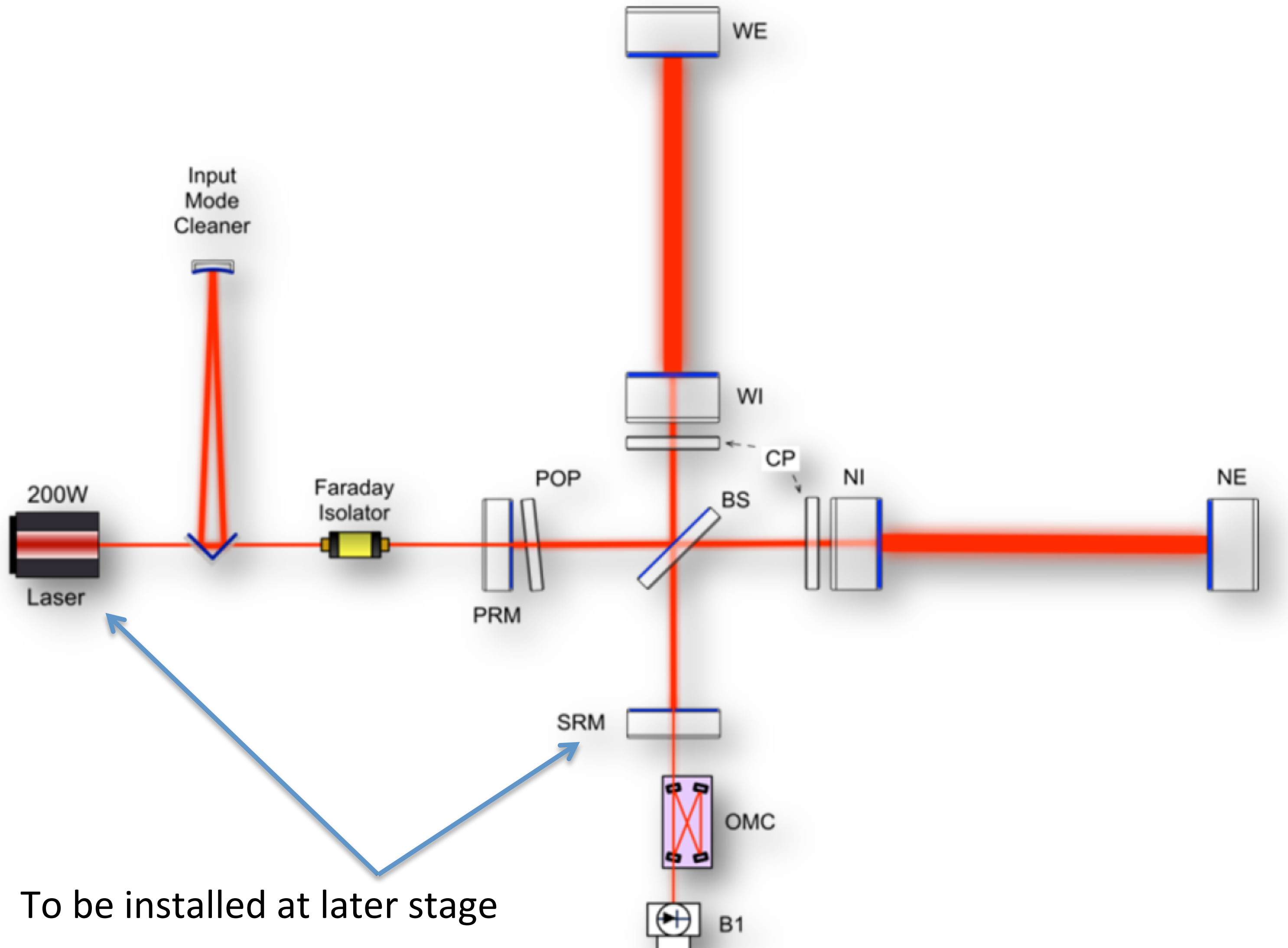
Advanced Virgo

- Advanced Virgo (AdV): upgrade of the Virgo interferometric detector
- Participated by scientists from France and Italy (former founders of Virgo), The Netherlands, Poland and Hungary
- Funding approved in Dec 2009 (21.8 ME + Nikhef in kind contribution)
- End of installation: July 2016
- Part of the international network (MoU with LSC)
- Short-term goal: join O2b in ~March 2017

6 European countries
20 labs, ~250 authors

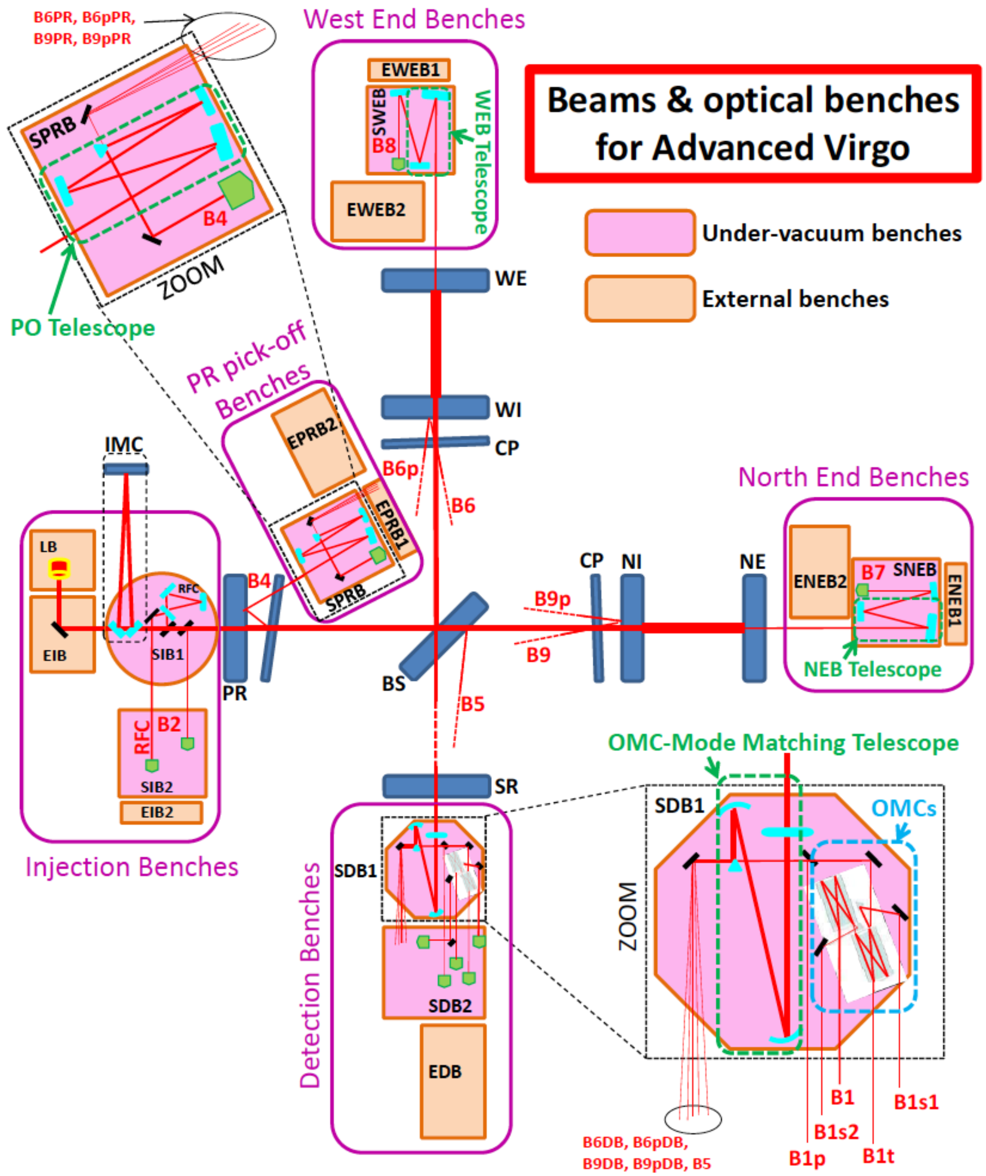
APC Paris
ARTEMIS Nice
EGO Cascina
INFN Firenze-Urbino
INFN Genova
INFN Napoli
INFN Perugia
INFN Pisa
INFN Roma La Sapienza
INFN Roma Tor Vergata
INFN Trento-Padova
LAL Orsay – ESPCI Paris
LAPP Annecy
LKB Paris
LMA Lyon
NIKHEF Amsterdam
POLGRAW(Poland)
RADBOUD Uni. Nijmegen
RMKI Budapest
Univ. of Valencia

AdV setup



To be installed at later stage

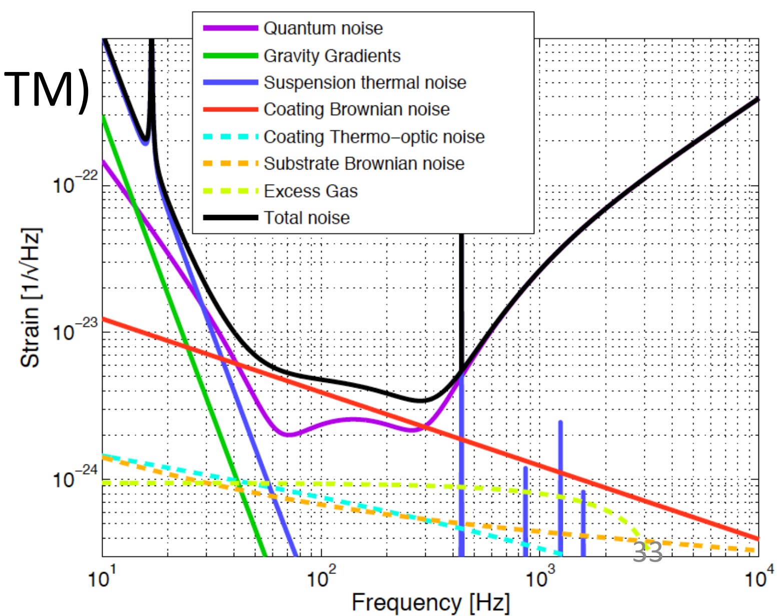
AdV setup



Beams & optical benches for Advanced Virgo
Under-vacuum benches
External benches
West End Benches
EWEB1
EWEB2
SWEB
B8
WEB Telescope
WE
WI
CP
B6p
B6
B6PR, B6pPR, B9PR, B9pPR
SPRB
B4
ZOOM
PO Telescope
PR pick-off Benches
EPRB2
EPRB1
IMC
LB
EIB
RFC
SIB1
RFC
B2
SIB2
EIB2
Injection Benches
PR
BS
B9p
B9
B5
CP
NI
NE
North End Benches
ENEB2
B7
SNEB
ENEB1
NEB Telescope
OMC-Mode Matching Telescope
SR
SDB1
OMCs
ZOOM
SDB2
EDB
Detection Benches
B6DB, B6pDB, B9DB, B9pDB, B5
B1
B1s1
B1s2
B1p
B1t

AdV challenges

- Reducing thermal noise:
  - increased beam size @ input TM (2.5 x higher)
  - improved mirrors' planarity (16 x better)
  - Improved coatings for lower losses (7 x better)
- Reducing quantum noise:
  - Increased finesse of arm cavities (9 x higher than iVirgo, 3 x higher than Virgo+)
  - High power laser (16 x more input power)
  - Heavier test masses (2 x heavier)
- Seismic isolation:
  - iVirgo superattenuators compatible with AdV specs
  - adapted for new payload (added mass and complexity)
  - new electronics
- Thermal compensation (100 x higher power on TM)
  - ring heaters
  - double axicon CO_2 actuators
  - CO_2 central heating
- Better vacuum (10^{-9} instead of 10^{-7})
- Stray light control
  - Suspended optical benches in vacuum
  - New set of baffles



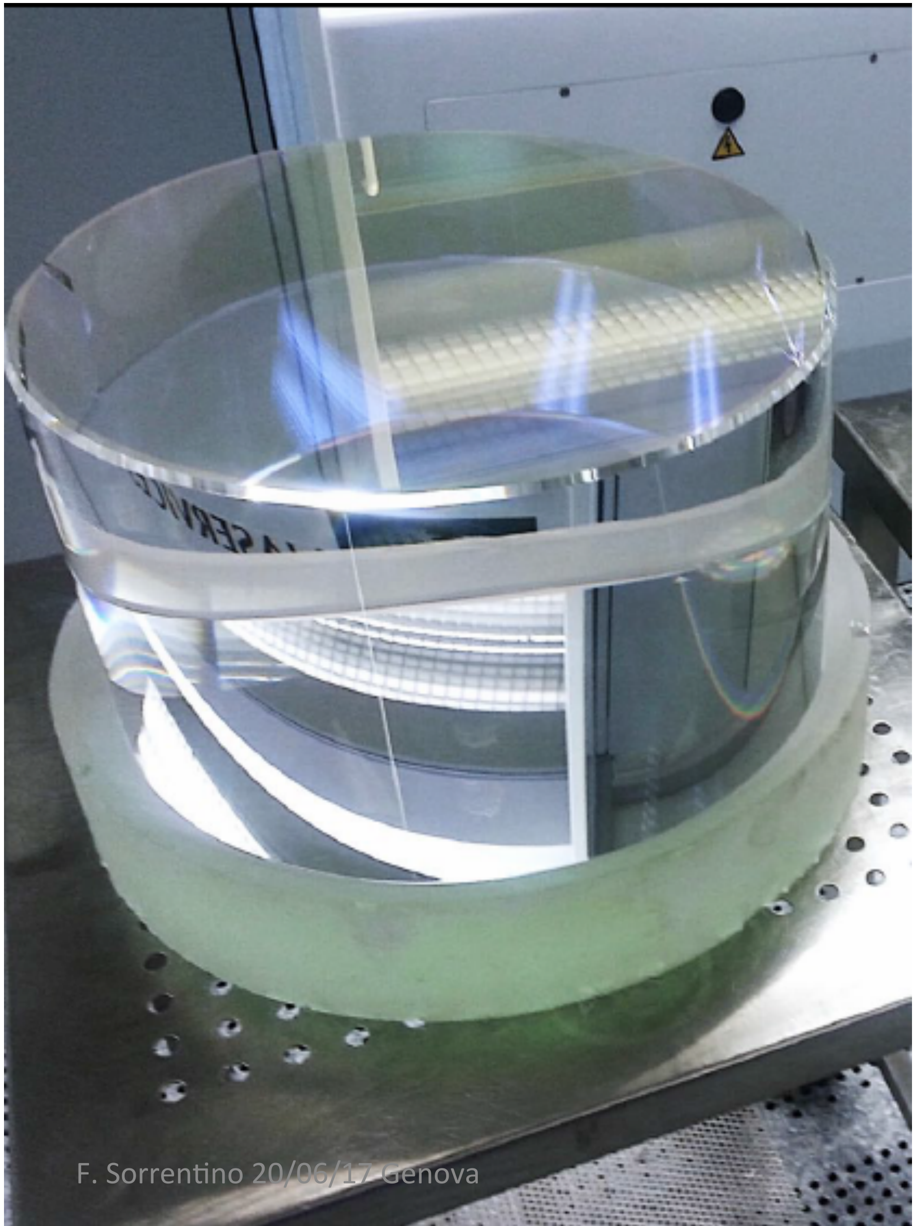
AdV vs initial Virgo

Subsystem and Parameters	AdV design (TDR)	Initial Virgo
Sensitivity		
Binary Neutron Star Inspiral Range	134 Mpc	12 Mpc
Anticipated Max Strain Sensitivity	$3.5 \cdot 10^{-24}/\sqrt{\text{Hz}}$	$4 \cdot 10^{-23}/\sqrt{\text{Hz}}$
Instrument Topology		
Interferometer	Michelson	Michelson
Power Enhancement	Arm cavities and Power Recycling	Arm cavities and Power Recycling
Signal Enhancement	Signal Recycling	n.a.
Laser and Optical Powers		
Laser Wavelength	1064 nm	1064 nm
Optical Power at Laser Output	>175 TEM_{00} W	20 W
Optical Power at Interferometer Input	125 W	8 W
Optical Power at Test Masses	650 kW	6 kW
Optical Power on Beam Splitter	4.9 kW	0.3 kW
Test Masses		
Mirror Material	Fused Silica	Fused Silica
Main Test Mass Diameter	35 cm	35 cm
Main Test Mass Weight	42 kg	21 kg
Beam Splitter Diameter	55 cm	23 cm
Test Mass Surfaces and Coatings		
Coating Material	Ti doped Ta_2O_5	Ta_2O_5
Roughness*	< 0.1 nm	< 0.05 nm
Flatness	0.5 nm RMS	< 8 nm RMS
Losses per Surface	37.5 ppm	250 ppm (measured)
Test Mass RoC	Input Mirror: 1420 m End Mirror: 1683 m	Input Mirror: flat End Mirror: 3600 m
Beam Radius at Input Mirror	48.7 mm	21 mm
Beam Radius at End Mirror	58 mm	52.5 mm
Finesse	443	50
Thermal Compensation		
Thermal Actuators	CO_2 Lasers and Ring Heater	CO_2 Lasers
Actuation points	Compensation plates and directly on mirrors	Directly on mirrors
Sensors	Hartmann sensors and phase cameras	n.a.

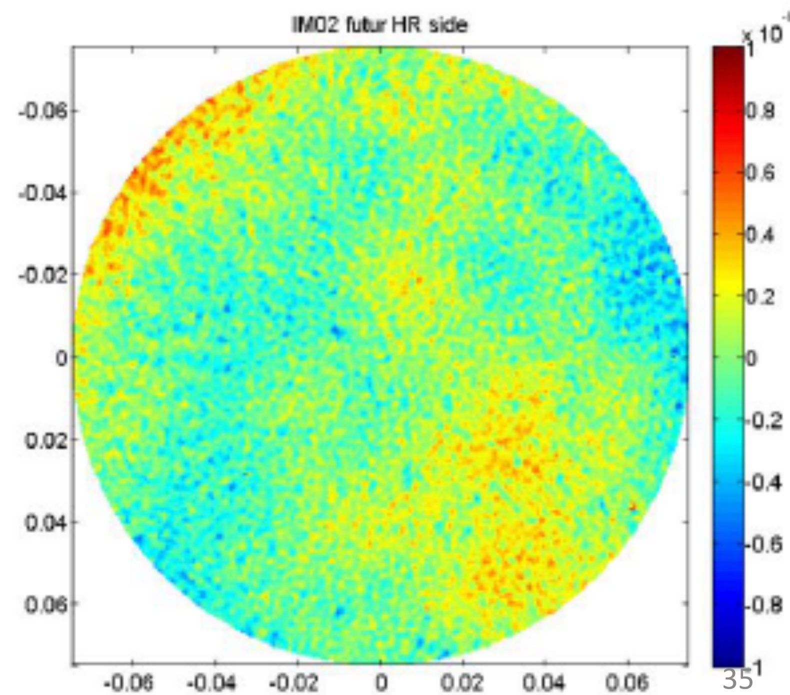
Subsystem and Parameters	AdV design (TDR)	Initial Virgo
Suspension		
Seismic Isolation System	Superattenuator	Superattenuator
Degrees of Freedom of Inverted Pendulum Inertial Control	6	4
Test mass suspensions	Fused Silica Fibres (optimized geometry)	Steel Wires
Vacuum System		
Pressure	10^{-9} mbar	10^{-7} mbar
Injection System		
Input mode cleaner throughput	>96%	85% (meas.)
Detection System		
GW Signal Readout	DC-Readout	Heterodyne (RF)
Output Mode Cleaner Suppression	RF Sidebands and Higher Order Modes	Higher Order Modes
Main Photo Diode Environment	in Vacuum	in Air
Lengths		
Arm Cavity Length	3 km	3 km
Input Mode Cleaner	143.424 m	143.574 m
Power Recycling Cavity	11.952 m	12.053 m
Signal Recycling Cavity	11.952 m	n.a.
Interferometric Sensing and Control		
Lock Acquisition Strategy	Auxiliary Lasers (different wavelength)	Main Laser
Number of RF Modulations	3	1
Schnupp Asymmetry	23 cm	85 cm
Signal Recycling Parameter		
Signal Recycling Mirror Transmittance	20 %	n.a.
Signal Recycling Tuning	0.35 rad	n.a.

From AdV TDR
https://tds.ego-gw.it/?content=3&r=9317

Mirrors

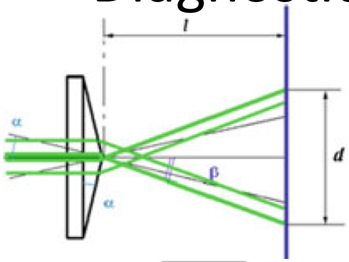


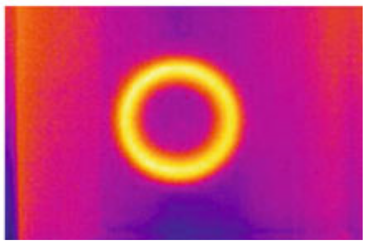
- Low mechanical losses
- Low optical absorption
- Low scattering
- 42 kg, 35 cm diam., 20 cm thick
- Flatness < 0.5 nm rms
- Roughness < 0.1 nm rms
- Absorption < 0.5 ppm

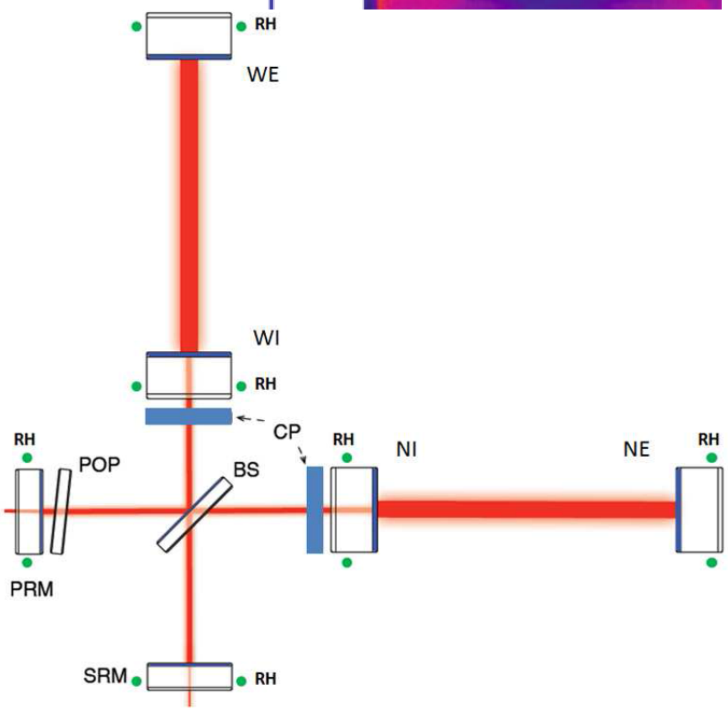


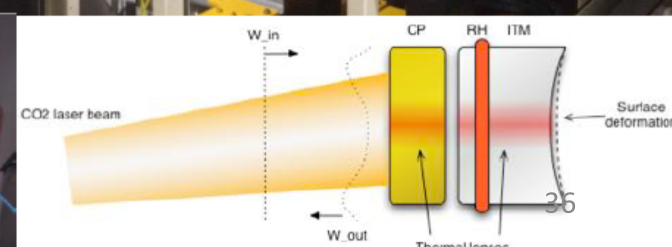
Thermal compensation

- Double axicon for better thermal lens correction
- Compensation plates to reduce CO_2 laser noise coupling
- Ring heater to tune mirror RoCs
- Diagnostics: Hartmann sensor & phase cameras



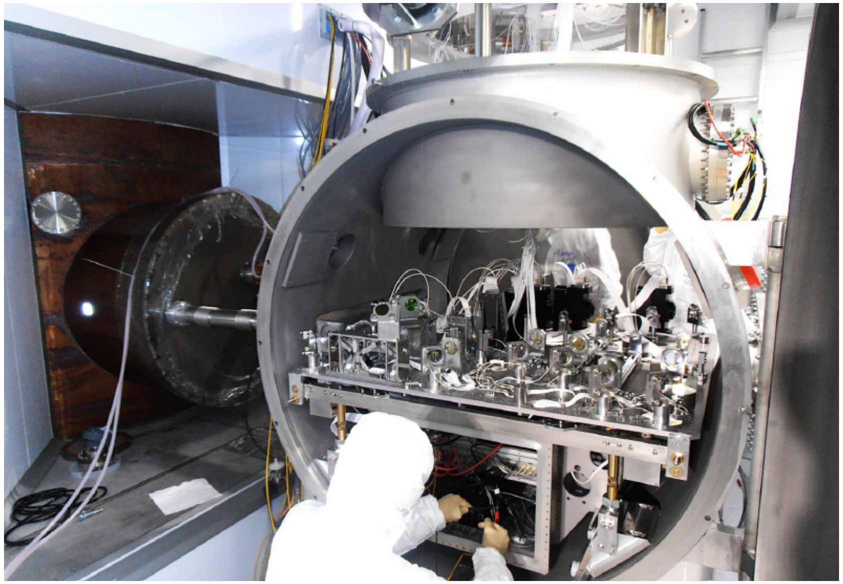


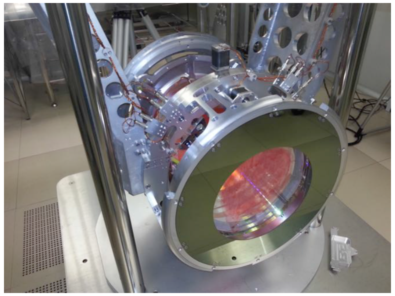


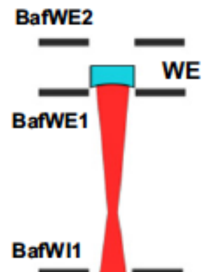


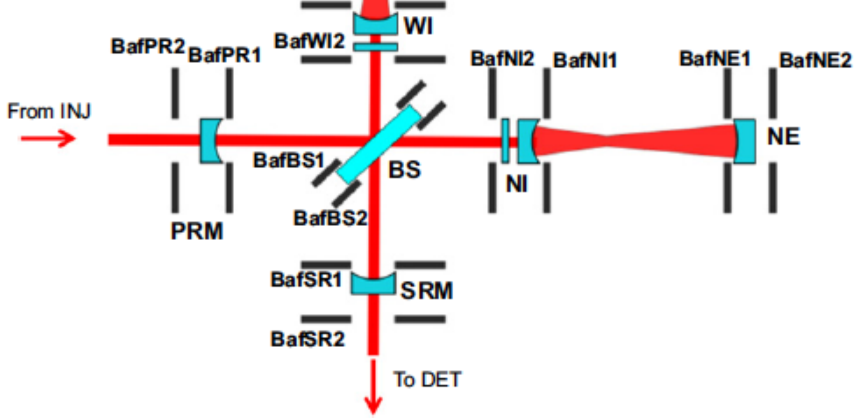
Stray light control

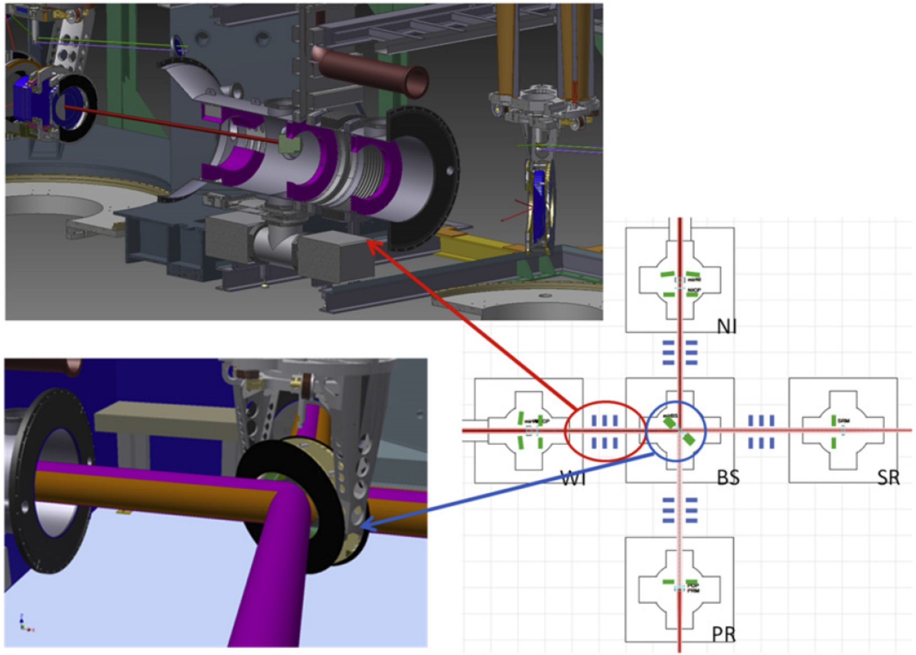
- Reducing amount of scattered light
  - 320 baffles welded to pipes
- Reduce relative motion between scattering surfaces and detection photodiodes
  - Baffles integrated on each suspended payload
  - Photodiodes hosted on suspended benches in vacuum





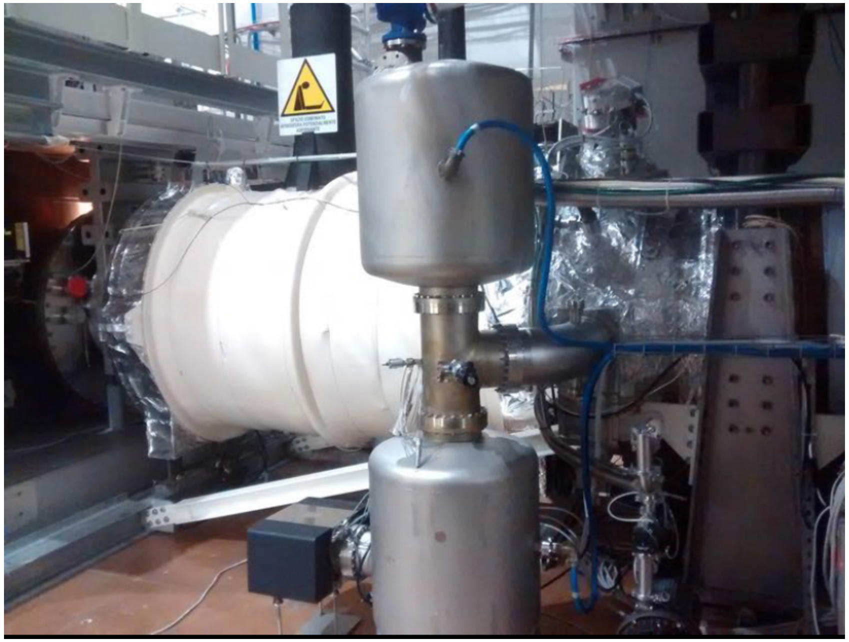






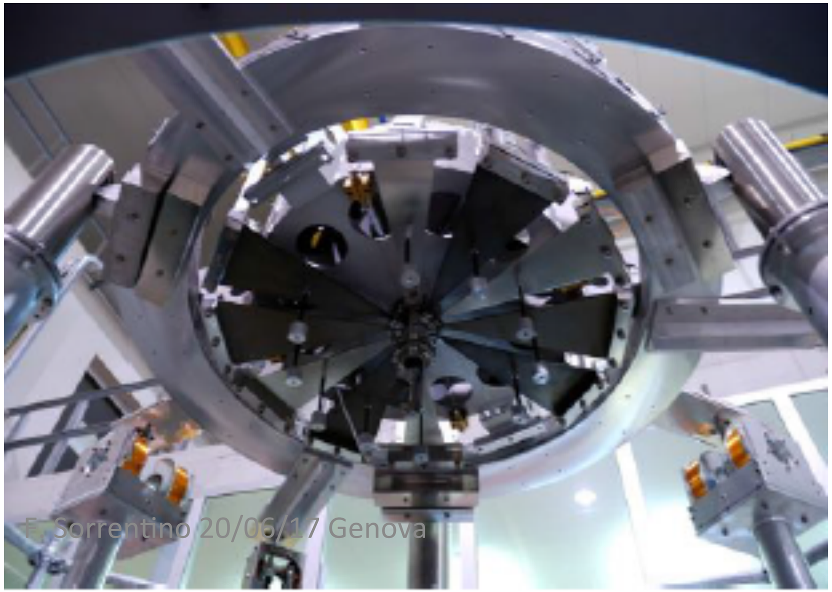
Vacuum

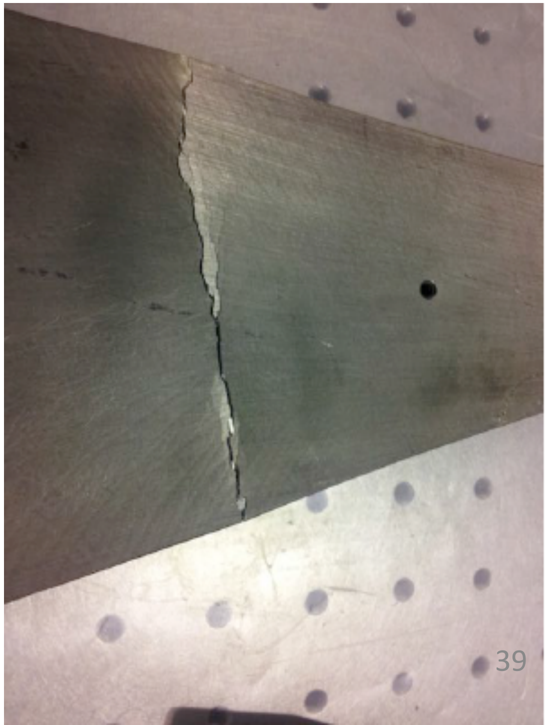
- With iVirgo vacuum level (10^{-7} mbar, dominated by H_2O) phase noise from background gas would limit AdV sensitivity
- Need to reduce phase noise by a factor 10 => improve vacuum by a factor 100 (scaling with √P)
- Backing arm tubes already tested to 10^{-9} mbar (dominated by hydrogen)
- Backing TM towers not opportune
- Large cryo-traps close to towers



Integration issues: broken blades

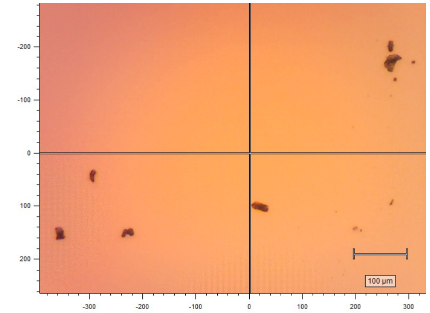
- At end 2015, 13 maraging blades of seismic filters in superattenuators were found broken
- We identified the cause of failure in hydrogen embrittlement of the steel
- We replaced about ½ of the blades
- We prepared a new stock

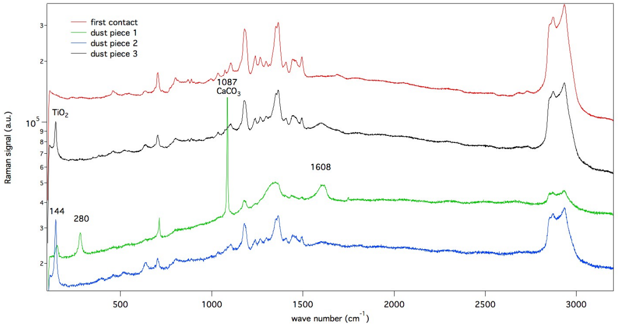


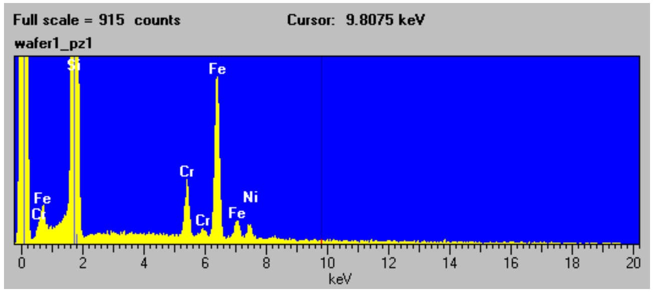


Monolithic suspensions issue

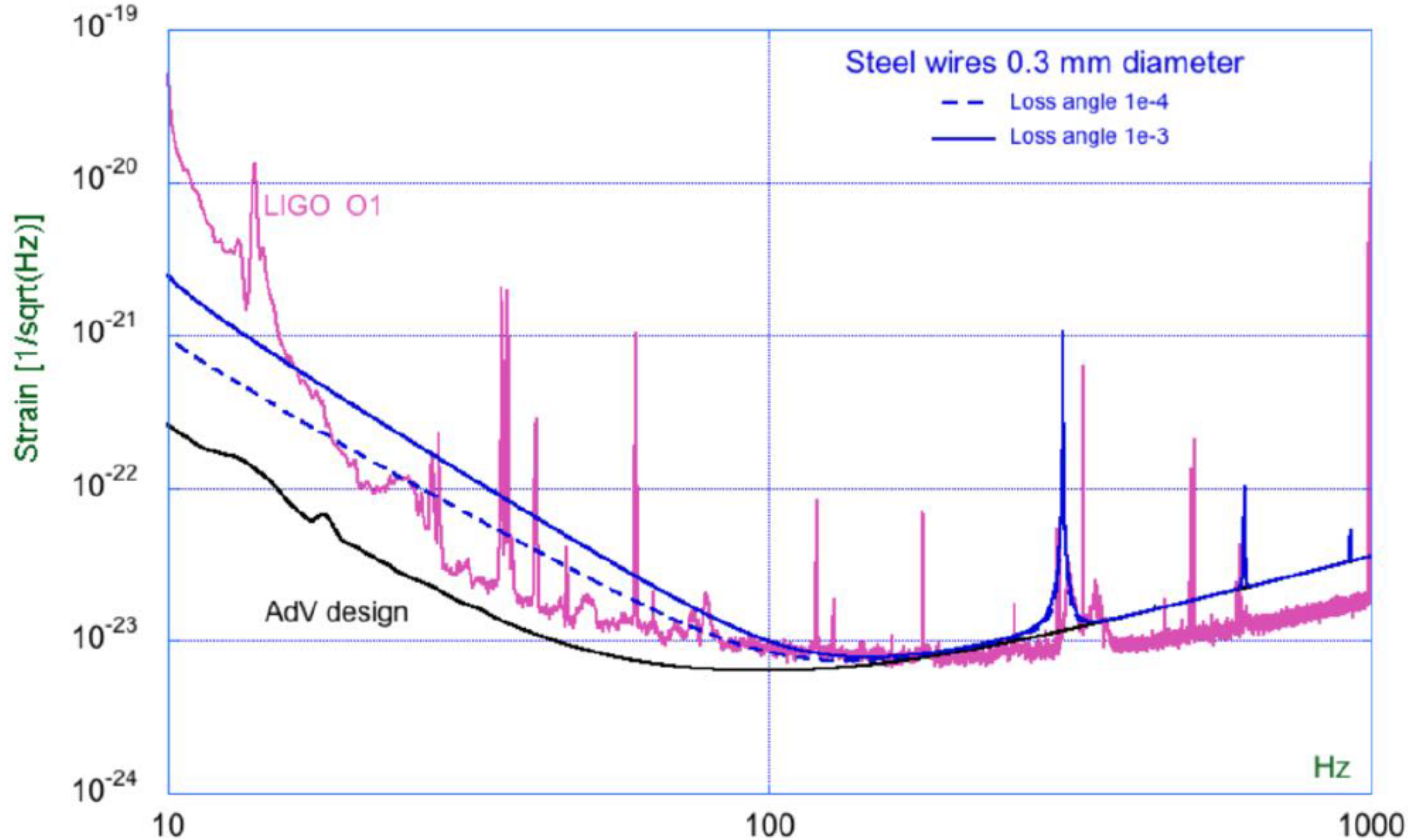
- Repeated breaking of monolithic suspensions under vacuum
- Temporary solution for O2: steel wires
- Deep investigation to find the causes of failure and possible solutions
  - Failure of glass anchors excluded by microscope analysis of fractures
    - Breaking always occurred at the level of the fibers
  - Basic mechanism of fiber breaking under vacuum identified
    - fast dust particles hit the fibre and produce fractures
    - In vacuum large velocities are possible, given an initial momentum
    - some pumping/venting cycles using scroll pumps provide significant dust levels in chamber
    - SEM and μ-Raman analysis of dust to understand origin
- Improvements on vacuum system: separate pumping and venting pipes
- Risk mitigation: metal shields around fibers





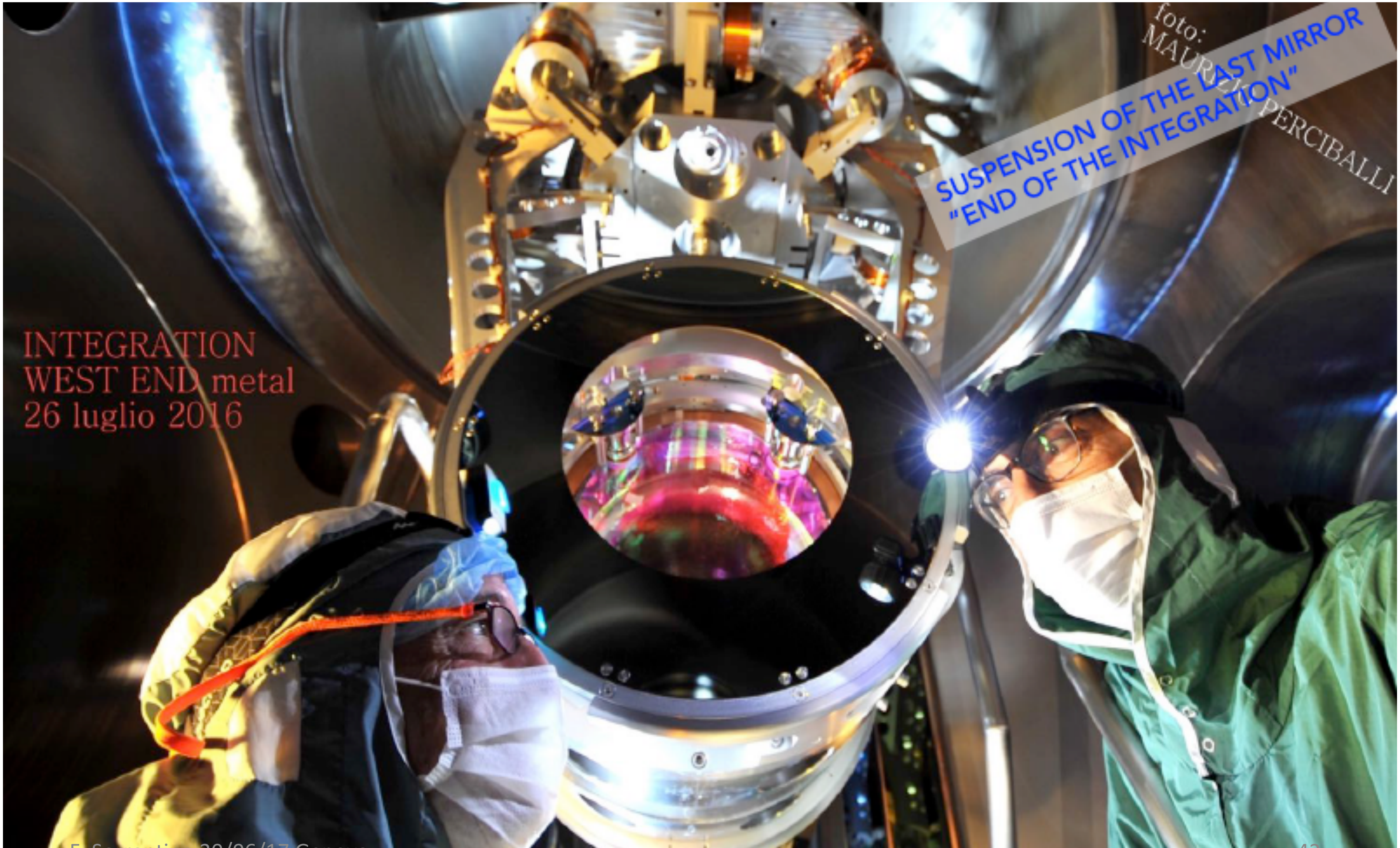


Target sensitivity for O2



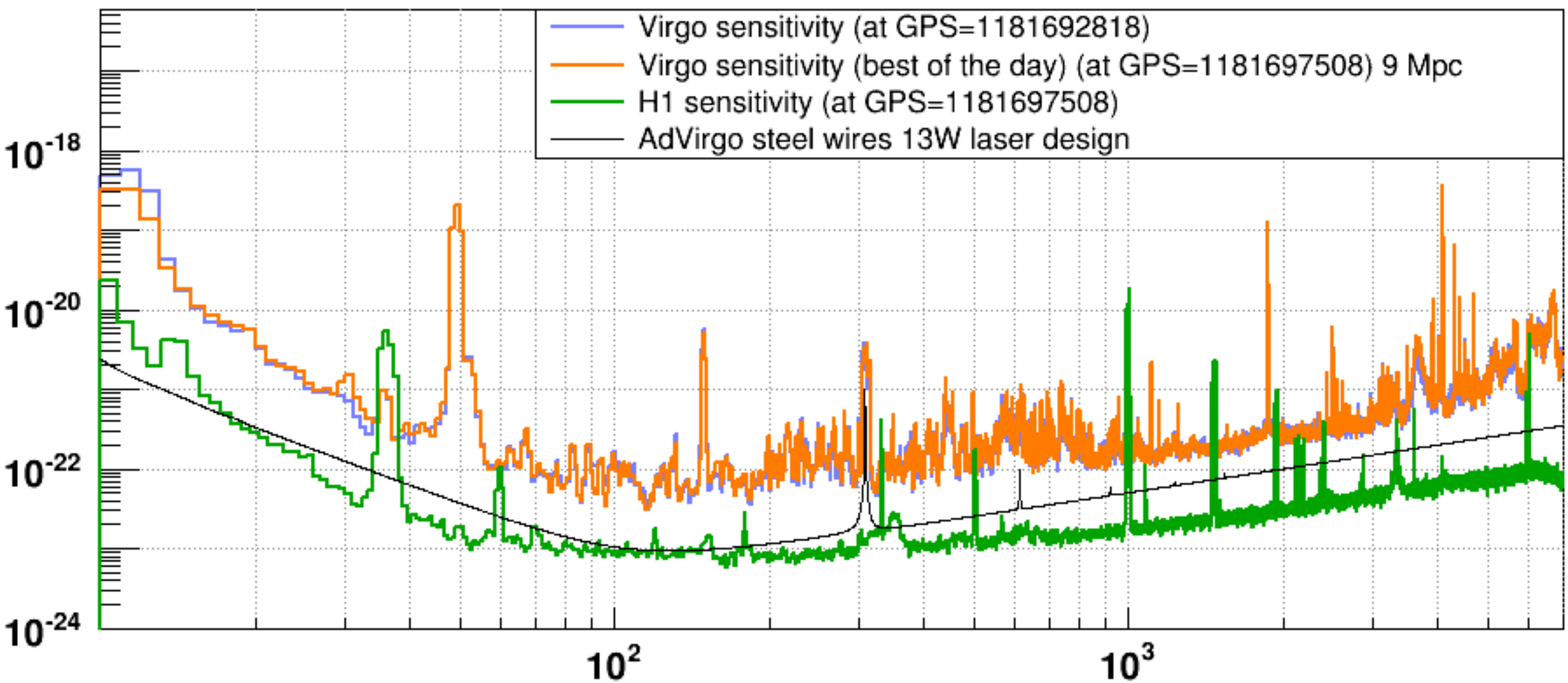
Inspiral range (Mpc), steel wires on 4 TM, ϕ = 1e-4 (1e-3)	
BNS	60 (45)
BBH	313 (202)

AdV installation concluded



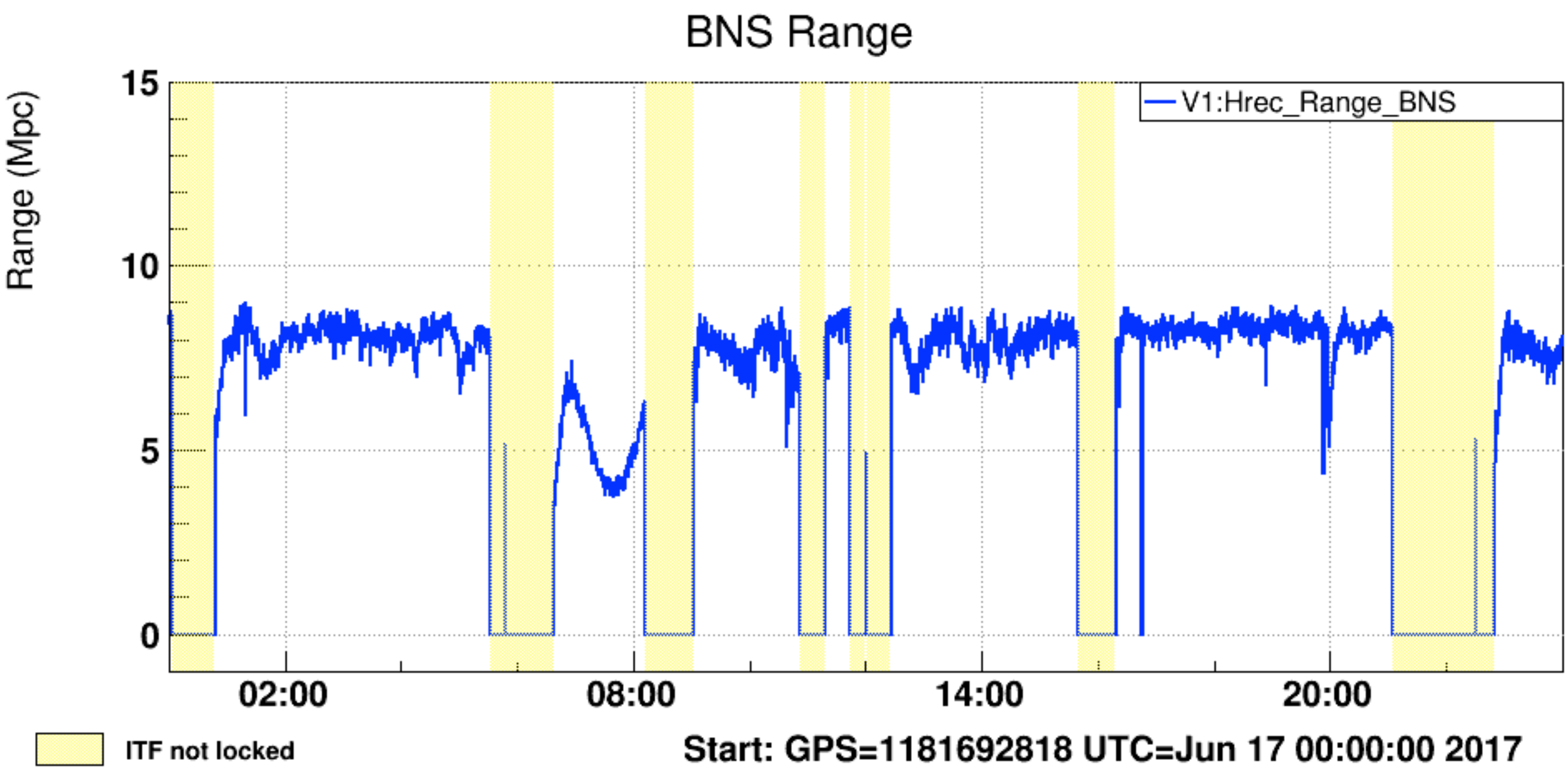
Current status

- Current sensitivity is at the level of Virgo+, about a factor 10 from LIGO
- Expected to improve by about a factor 2 within a few weeks, mostly by noise hunting



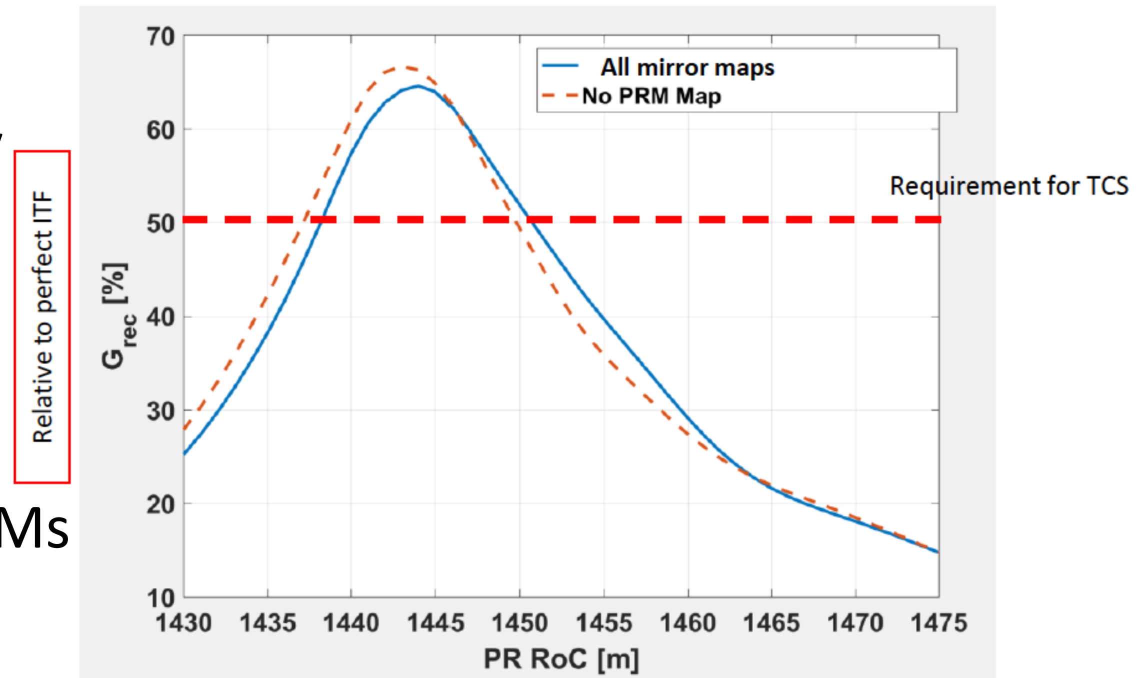
Current status

- ER11 started on last week-end
- First joint operation of three advanced detectors!



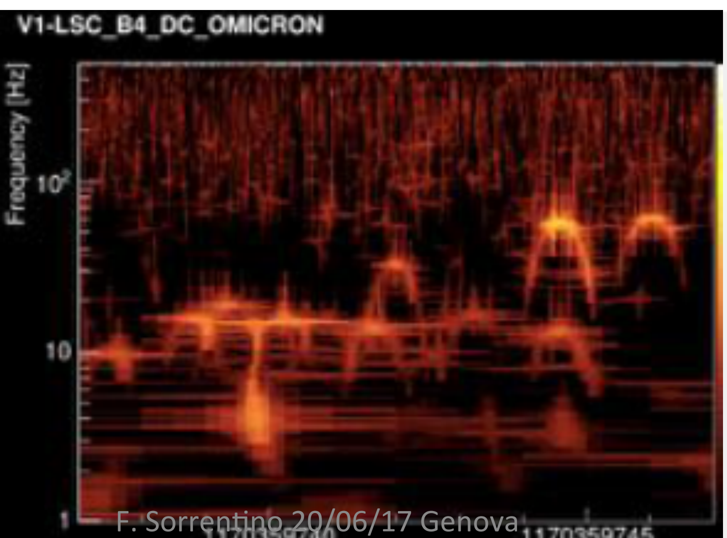
Commissioning challenges

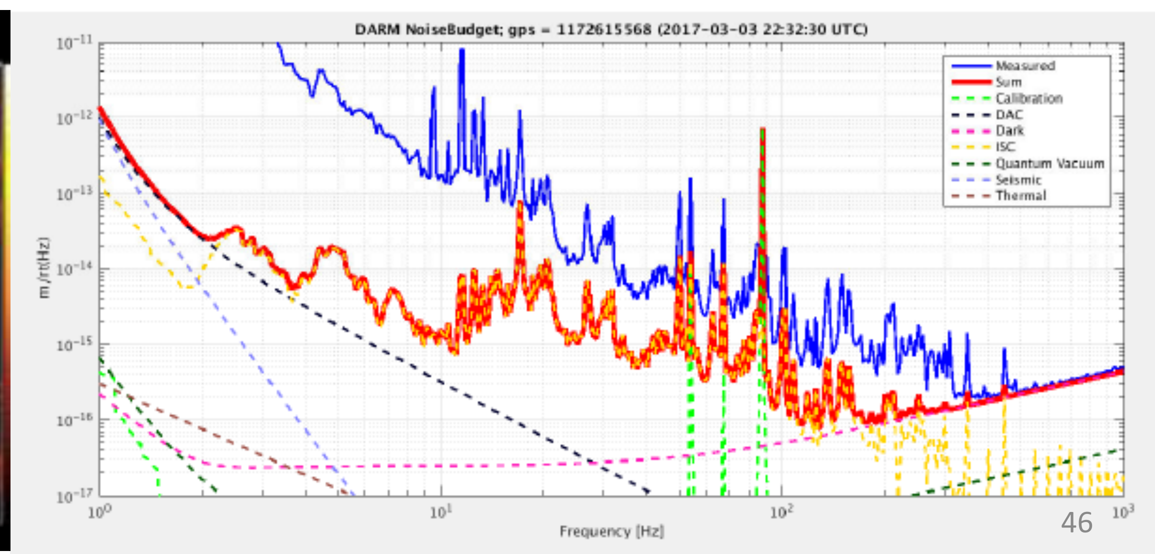
- AdV optical configuration is challenging: marginally stable cavities
- Recent measurement of critical optical parameters
  - PRCL gain for carrier and sidebands
  - PRCL length
  - Schnupp's asymmetry
  - Arm cavity finesse
  - Arm cavity losses
- Optical simulations
  - TCS induced RoC in ITMs
  - Recycling gain vs RoC



Noise hunting

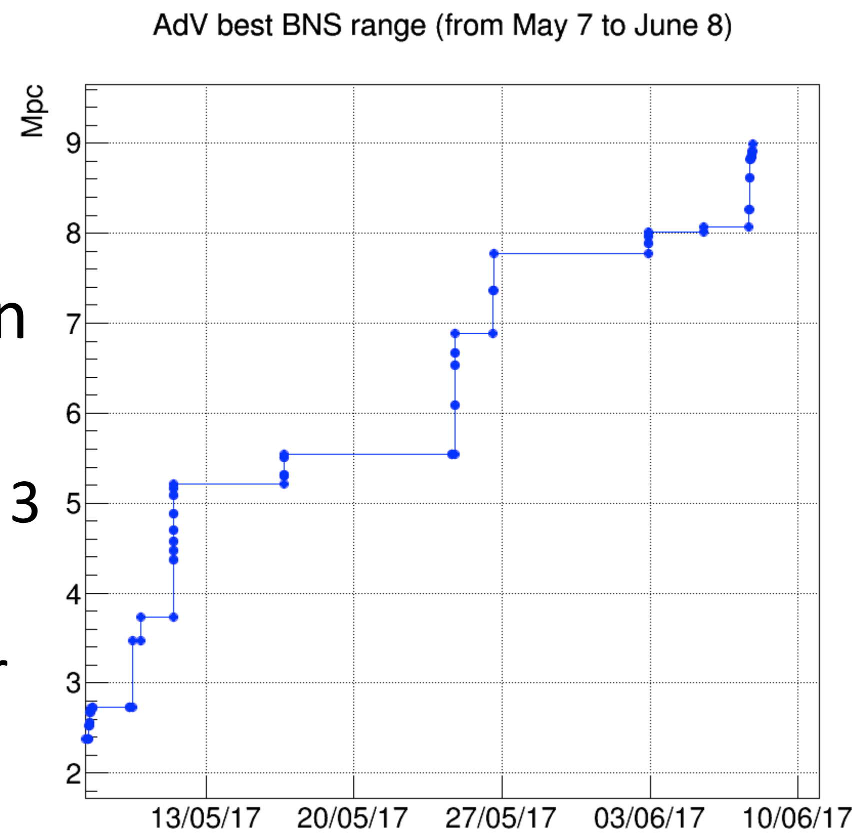
- Systematic correlation of all environmental channels with ISC signals
  - several families of scattered light glitches identified
  - some e.m. noise couplings identified and removed
- Noise budget developed
  - Preliminary data from first dark fringe locks
  - Currently dominated by control noise
  - Best sensitivity @400 Hz





Short term plan

- In 4÷6 weeks, before joining O2
  - Noise hunting and minor upgrades
  - Goal is to reach a BNS range around 20 Mpc
- Data taking in science mode in this configuration for O2
  - Acquire data with a network of 3 detectors
  - Performance check on detector
  - To identify technical noises limiting the sensitivity

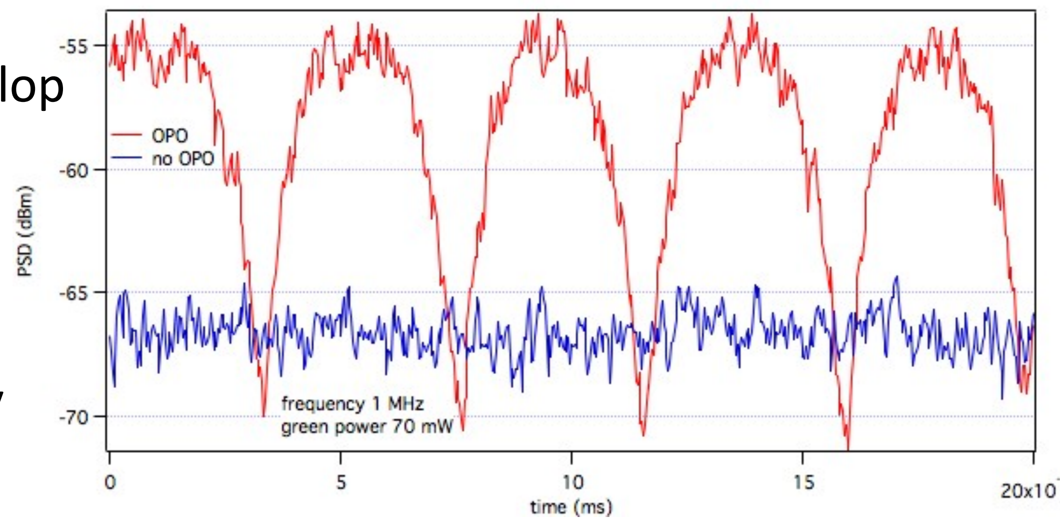


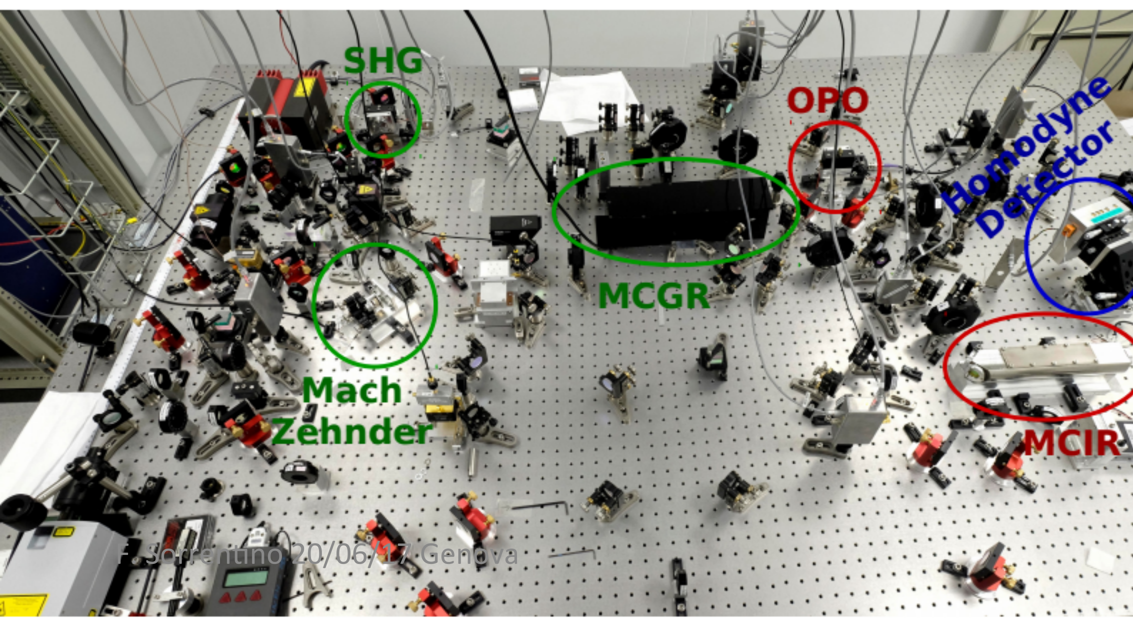
Medium term plan

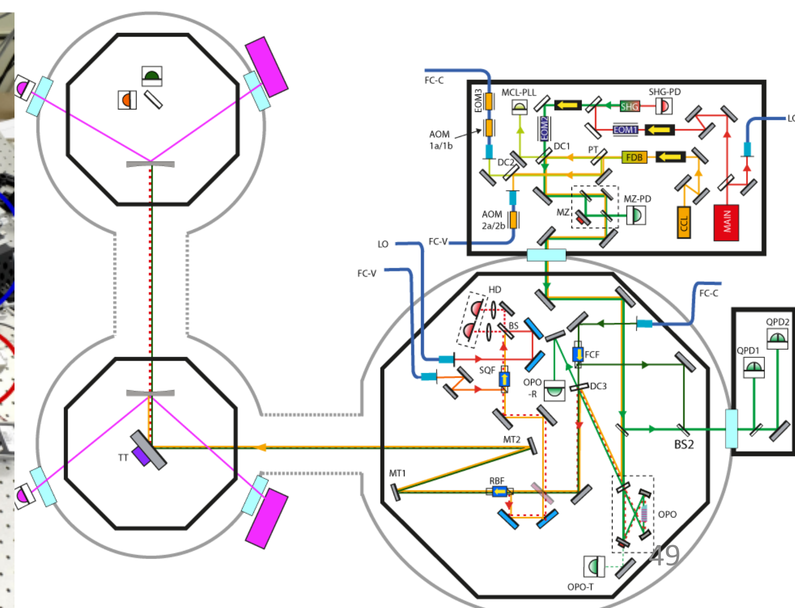
- Further commissioning after the end of O2
  - Mitigate technical noises
  - Put TCS in operation to cope with unstable optical cavities
- Further changes possibly implemented before O3
  - **Monolithic suspensions (4 FP payloads)**
  - **Frequency independent squeezer**
  - Signal recycling
  - High power laser
- **Priority** with respect to sensitivity gain/impact on commissioning
- Need some commissioning time after each installation

Squeezing in AdV

- Originally not foreseen in TDR
- Working group since 2013 to develop a prototype optical bench for frequency independent squeezing
  - Assembled and currently operating @EGO
- In parallel conceptual design developed @ CALVA for frequency dependent squeezing with a filter cavity

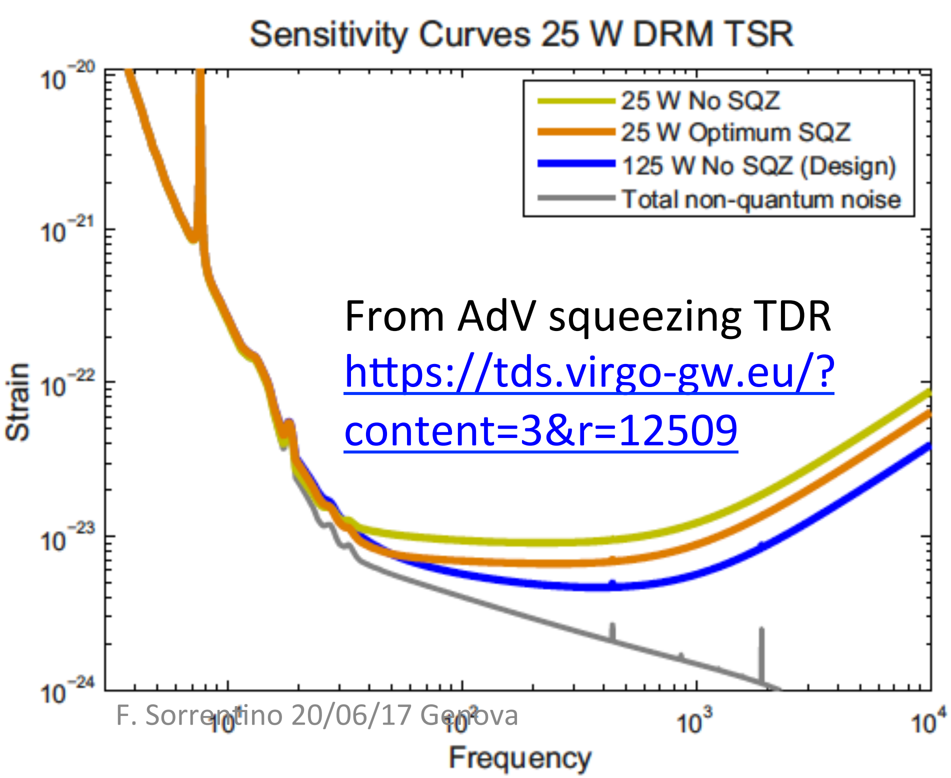




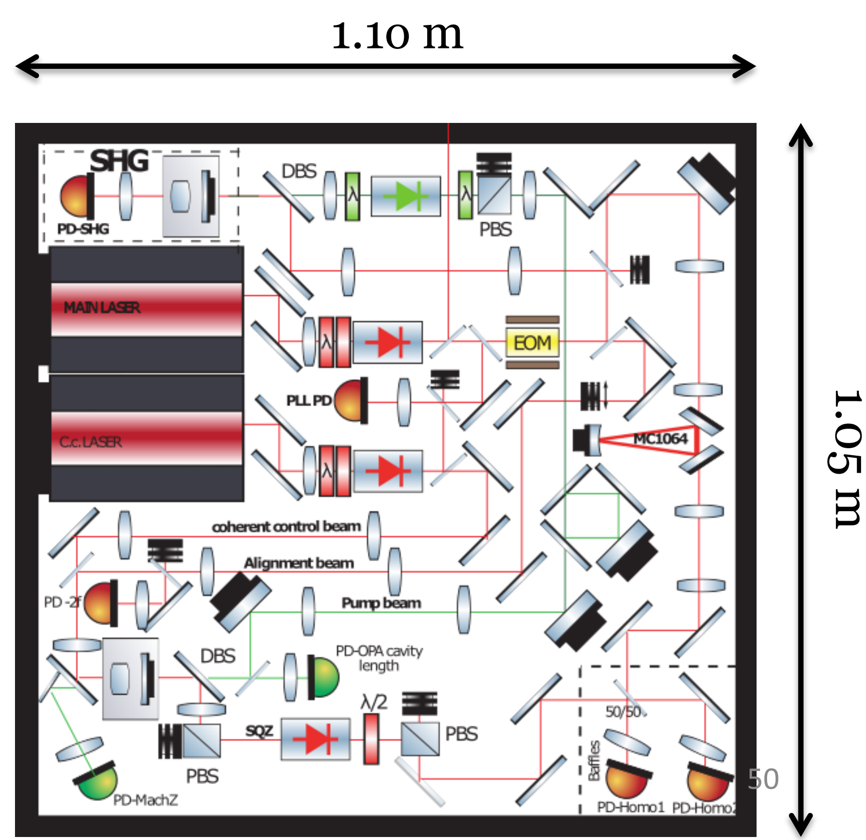


Squeezing in AdV

- Recent proposal by GEO to provide a benchtop squeezer (15 dB frequency independent)
- A working group was set up to manage the integration in AdV before O3



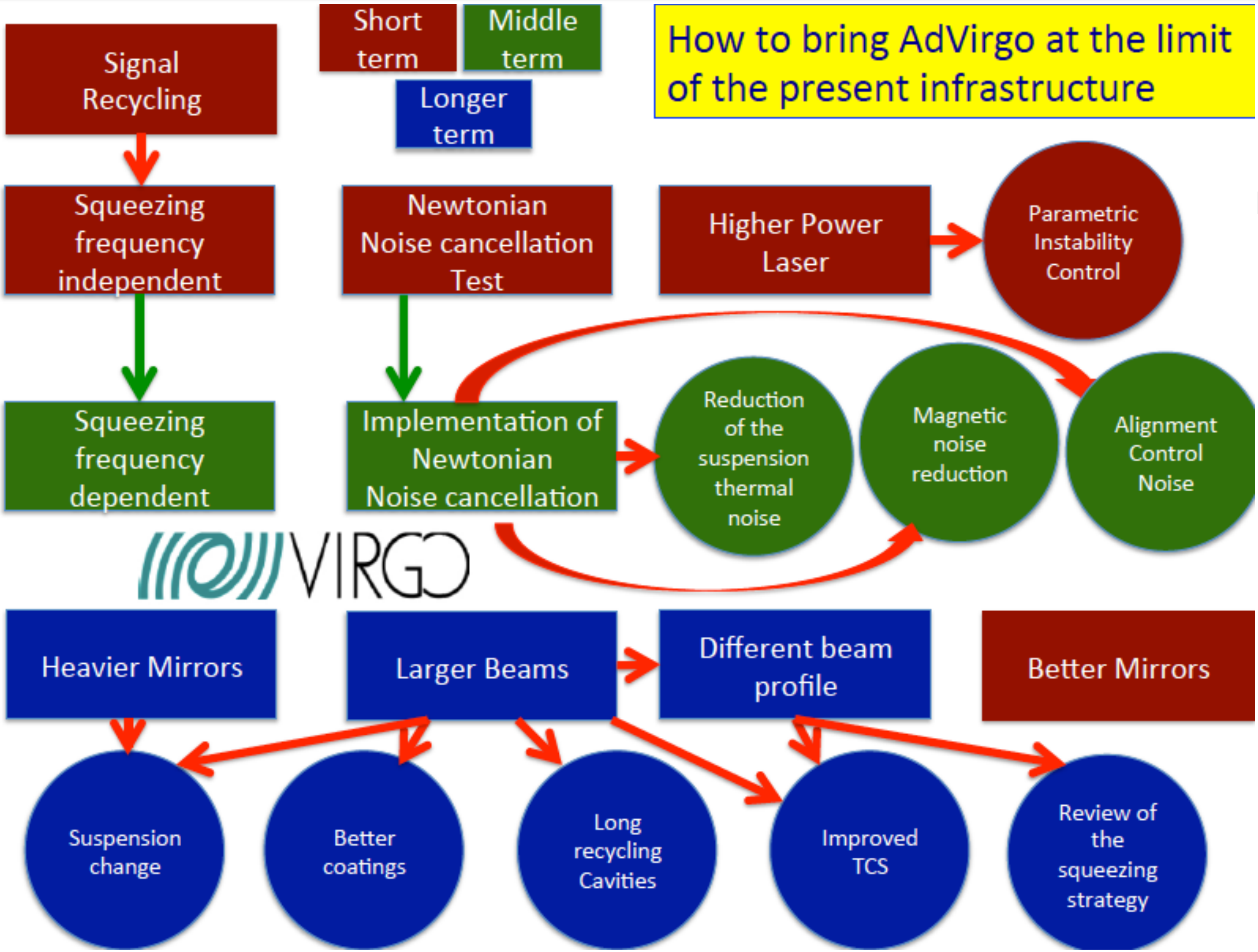
From AdV squeezing TDR
https://tds.virgo-gw.eu/?content=3&r=12509



After the AdV project

- Goal for next decade: exploit the scientific potential of AdV, and pave the way to 3rd generation
- 2017÷2018: upgrades towards O3
- 2018÷2022: successive improvements forward design sensitivity, pursue long and high duty cycle operation
- After 2022: upgrades in current infrastructure, beyond AdV design sensitivity and in view of 3G infrastructure (E.T.)
  - Frequency dependent squeezing
  - NN cancellation
  - coatings

AdV+


Short term
Middle term
Longer term
How to bring AdVirgo at the limit of the present infrastructure
Signal Recycling
Squeezing frequency independent
Newtonian Noise cancellation Test
Higher Power Laser
Parametric Instability Control
Squeezing frequency dependent
Implementation of Newtonian Noise cancellation
Reduction of the suspension thermal noise
Magnetic noise reduction
Alignment Control Noise
Heavier Mirrors
Larger Beams
Different beam profile
Better Mirrors
Suspension change
Better coatings
Long recycling Cavities
Improved TCS
Review of the squeezing strategy

F. Ricci

Conclusions

- GW170104
  - No dramatically new features, more solid case for stellar BBH systems, detection rates confirmed, limits on GR tests improved
- Future of GW detectors
  - Next 3÷5 yr: reach aLIGO and AdV design sensitivity, first operation of Kagra
  - increased observation time, tens of BBH detections expected, possible detection of other sources
  - In 10 yr: extended network of 2nd generation detectors: Kagra, iLIGO
  - In 15÷20 yr: LISA mission, set up of 3rd generation
- Advanced Virgo:
  - installation completed in July 2016
  - Commissioning in advanced status
  - Short term: join O2 in a few weeks
  - Medium term: upgrades towards O3
  - Long term: reliable operation at AdV design sensitivity, and plan for R&D beyond AdV